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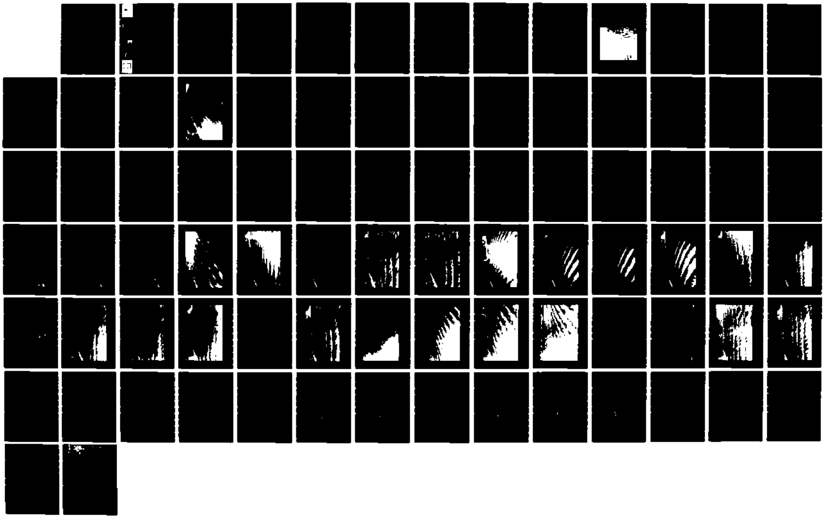

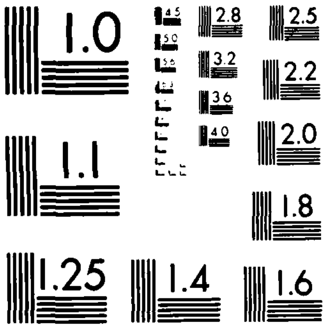

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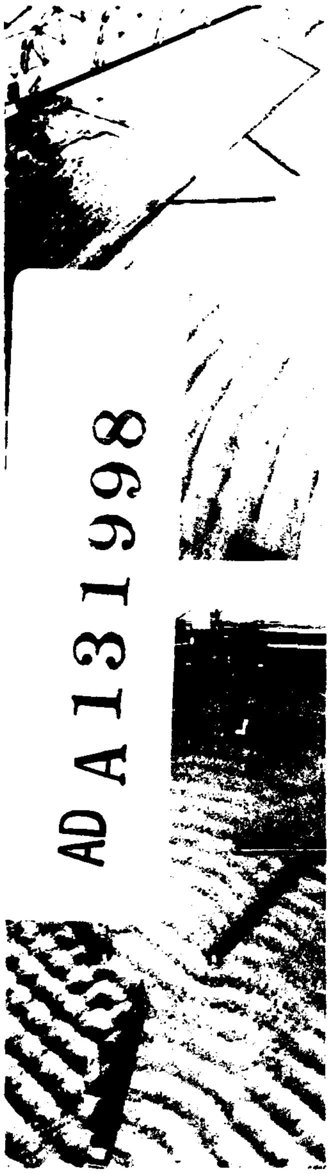

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TECHNICAL REPORT HL-83-11

EDGEWATER MARINA, CLEVELAND, OHIO DESIGN FOR WAVE PROTECTION

Hydraulic Model Investigation

by

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July 1983
Final Report

Approved For Public Release; Distribution Unlimited

Prepared for U. S. Army Engineer District, Buffalo
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A 1:100-scale (undistorted) hydraulic model of the western portion of Cleveland Harbor, which was used initially to determine effects of proposed improvements at the Cleveland Harbor main entrance with respect to ship maneuverability, wave and current action, and riverflow conditions was used to determine the effects of various improvement plans with respect to wave and current action at Edgewater Marina, located at the western boundary of Cleveland Harbor. Improvements at Edgewater Marina consisted

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of modifications to the harbor entrance and channel, installation of new breakwaters, modifications to the existing structures, and installation of rubble absorbers in the harbor. A 120-ft-long wave generator and an Automated Data Acquisition and Control System were utilized in model operation. It was concluded from test results that:

a. For existing conditions, rough and turbulent wave and current conditions existed in the harbor entrance and basin during periods of storm wave attack.

b. Of the improvement plans tested with the new breakwater installed at the existing entrance and the east breakwater raised to an elevation of +9.5 ft (Plans 1-1I), Plan 1H appeared to be optimal with respect to wave protection and construction costs.

c. Of the improvement plans tested with absorber installed adjacent to the entrance structures and the east breakwater raised to an elevation of +9.5 ft (Plans 2-2C), Plan 2C appeared to be optimal with respect to wave protection and construction costs.

d. Of the improvement plans tested with the existing entrance closed and raised to an elevation of +9.5 ft, the east breakwater raised to an elevation of +9.5 ft, and a new entrance installed through the Cleveland Harbor west breakwater (Plans 3-3C), Plans 3B and 3C appeared to be optimal with respect to wave protection in the marina; however, wave heights in the Cleveland Harbor West Basin increased significantly.

e. Of the improvement plans tested with the curved portion of the Edgewater breakwater replaced with randomly placed stone and the east breakwater raised to an elevation of +15 ft (Plans 4-4E), Plans 4C and 4E appeared to be optimum with respect to wave protection afforded and construction costs.

f. For any improvement plan to be effective (i.e., wave heights reduced to 1.0 ft or less in the marina) a portion of the existing Edgewater breakwater (that portion adjacent to the existing sheet-pile wall) will have to be either raised or increased in width.

g. The installation of any of the optimal improvement plans tested should reduce or eliminate hazardous wave-induced currents in the basin during the boating season (spring, summer, and fall).

PREFACE

A request for a model investigation of wave action at Edgewater Marina, Cleveland, Ohio, was initiated by the District Engineer, U. S. Army Engineer District, Buffalo (NCB), and authorization for the U. S. Army Engineer Waterways Experiment Station (WES) to perform the study was granted by the Office, Chief of Engineers, U. S. Army. Funds were authorized by NCB on 24 May 1982 and 2 December 1982.

The model study was conducted at WES during the period September-November 1982 by personnel of the Wave Dynamics Division, Hydraulics Laboratory, under the direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory; Mr. F. A. Herrmann, Jr., Assistant Chief of the Hydraulics Laboratory; and Mr. C. E. Chatham, Jr., Acting Chief of the Wave Dynamics Division. The tests were conducted by Mr. H. F. Acuff, Jr., Civil Engineering Technician, with the assistance of Mr. L. L. Friar, Electronics Technician, under the supervision of Mr. R. R. Bottin, Jr., Project Manager. This report was prepared by Messrs. Bottin and Acuff.

Prior to the model investigation, Mr. Bottin met with representatives of NCB and visited the Edgewater Marina site. During the course of the investigation, liaison between NCB and WES was maintained by telephone communications and monthly progress reports.

Messrs. Charlie Johnson of NCD, Denton Clark and Wiener Cadet of NCB, James Swartzmiller and Bob Lucas of the Ohio Department of Natural Resources, and Gary Eby and Roger Newberry of the Edgewater Marina Yacht Club visited WES to observe model operation and participate in a conference during the course of the model study.

The Cleveland Harbor model was initially constructed to determine the effects of proposed improvements at the Cleveland Harbor main entrance with respect to ship maneuverability, wave and current action, and riverflow conditions.

Commander and Director of WES during the conduct of this investigation and the preparation and publication of this was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
feet per second	0.3048	metres per second
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
square miles (U. S. statute)	2.589988	square kilometres

EDGEWATER MARINA, CLEVELAND, OHIO
DESIGN FOR WAVE PROTECTION

Hydraulic Model Investigation

PART I: INTRODUCTION

The Prototype

1. The city of Cleveland, Ohio, is located on the southern shore of Lake Erie, 110 miles* east of Toledo, Ohio, and 191 miles west of Buffalo, New York (Figure 1). With a population of 750,000 people, it is the largest city in Ohio and the tenth largest in the United States (USAEDB 1976).

2. Edgewater Marina, located on the western boundary of the city of Cleveland adjacent to Cleveland Harbor, was constructed in 1956. The

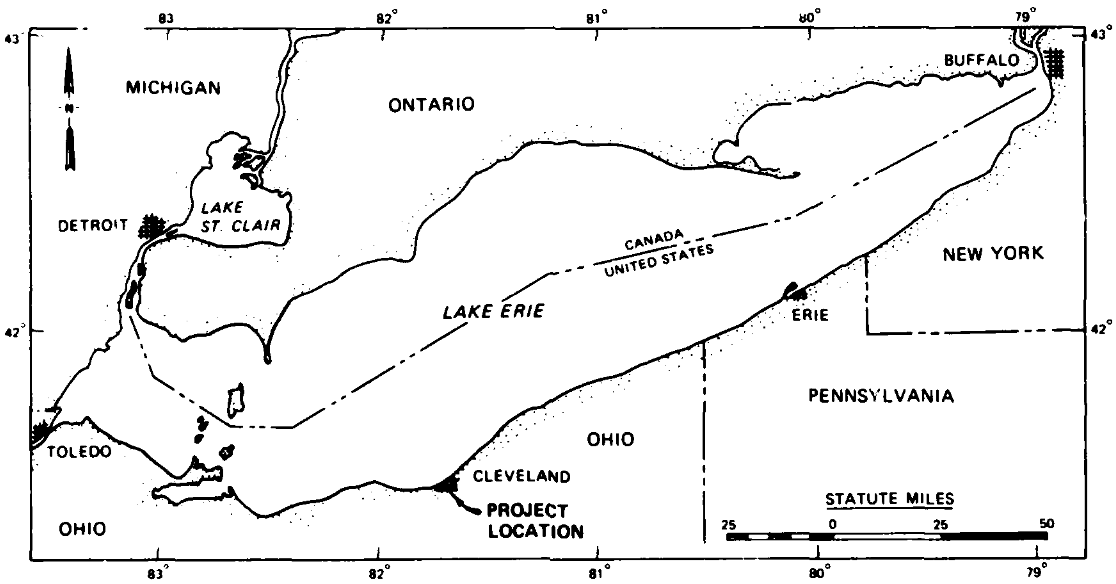


Figure 1. Project location

* A table of factors for converting U. S. customary units of measurement to metric (SI) is presented on page 3.

marina basin is essentially rectangular in shape, measuring approximately 1,550 ft by 850 ft, and accommodates mooring of over 600 boats. Harbor protection is provided by the Cleveland Harbor breakwater on the east and a rubble-mound breakwater (with sheet pile on the marina side) to the north. Facilities at Edgewater include a gas dock, boat storage and maintenance facilities, and a food concession stand. An aerial photograph of Cleveland Harbor and Edgewater Marina is shown in Figure 2.

Figure 2. Aerial photograph of Edgewater Marina (foreground) and Cleveland Harbor

The Problem

3. Since its construction, rough water in the marina has caused damage to harbor structures and boats moored to the docks. These rough wave conditions occur two to three times a year and appear to be due to short-period waves and surge in the marina basin related to major storm waves on Lake Erie. Waves in the basin reach 3 to 4 ft on occasion, with typical periods of 5 to 10 sec (Stanley Consultants 1979). Waves propagate through the harbor entrance and also overtop the existing breakwater. This results in a high level of wave energy within the basin, which is not dissipated but retained due to reflections from the existing vertical walls. These conditions have prohibited the optimum development of slips in the basin area, and insurance rates have increased substantially due to the risks involved.

Proposed Improvement Plans

4. Proposed improvements at Edgewater Marina consisted of one or more of the following:

- a. Modification of the channel entrance: This alternative would consist of the construction of a jetty extension to prevent wave energy from entering the marina.
- b. Marina basin modifications: This alternative would entail the placement of rubble wave absorber along the vertical walls in the basin and along the vertical entrance structures.
- c. Major structural alteration of the entrance: This alternative would involve closing off the present entrance and providing for a new entrance through the Cleveland west breakwater.

Purposes of the Model Study

5. The Cleveland Harbor model was originally constructed to determine the modifications necessary at the Cleveland Harbor west (main) entrance for the safe and efficient passage of 1,000-ft-long vessels (Bottin 1983).

6. Subsequent to testing for the Cleveland Harbor study, the U. S. Army Engineer District, Buffalo (NCB), requested that the U. S. Army Engineer Waterways Experiment Station (WES) conduct model tests at Edgewater Marina to:

- a. Determine the degree of wave protection afforded the basin as a result of the proposed modifications.
- b. Develop remedial plans, as necessary, for the alleviation of undesirable wave conditions.
- c. Determine if design modifications to the proposed plans could be made that would reduce construction costs significantly and still provide adequate wave protection.
- d. Determine wave-induced current conditions in the entrance and mooring area for the selected plan.

Wave-Height Criterion

7. Completely reliable criteria have not yet been developed for ensuring satisfactory navigation and mooring conditions in small-craft harbors during attack by waves. However, for the study reported herein, NCB specified that for an improvement plan to be acceptable, maximum wave heights in Edgewater Marina should not exceed 1.0 ft. This 1.0-ft criterion was established for waves occurring during the boating season (spring, summer, fall) with a 20-year recurrence interval.

PART II: THE MODEL

Design of Model

8. The Cleveland Harbor and Edgewater Marina model (Figure 3) was constructed to an undistorted linear scale of 1:100, model to prototype. Scale selection was based on such factors as:

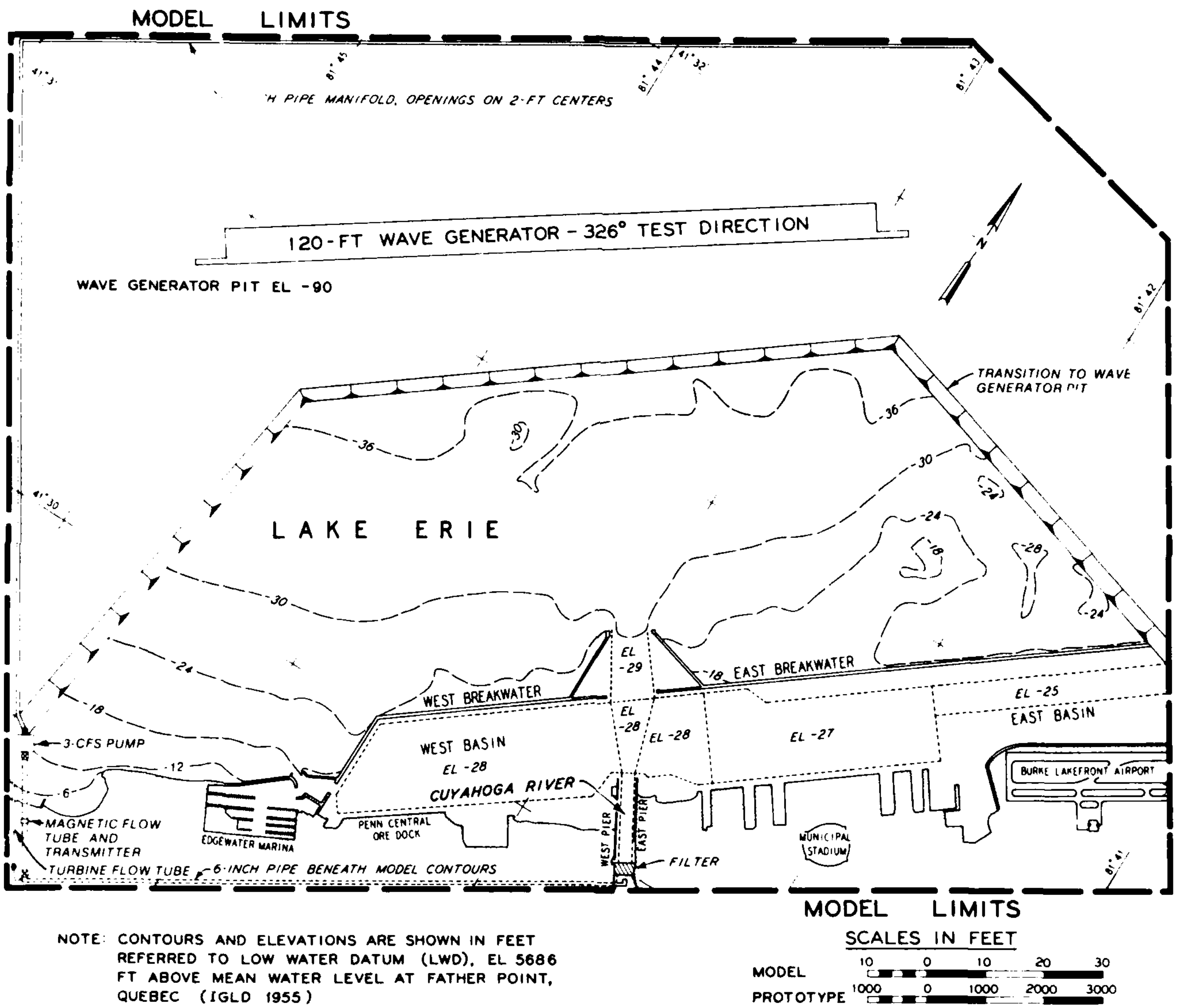
- a. Depth of water required in the model to prevent excessive bottom friction.
- b. Absolute size of model waves.
- c. Available shelter dimensions and area required for model construction.
- d. Efficiency of model operation.
- e. Available wave-generating and wave-measuring equipment.
- f. Model construction costs.

A geometrically undistorted model was necessary to ensure accurate reproduction of short-period wave and current patterns. Following selection of the linear scale, the model was designed and operated in accordance with Froude's model law (Stevens et al. 1942). The scale relations used for design and operation of the model were as follows.

Characteristic	Dimension*	Model: Prototype Scale Relation
Length	L**	$L_r = 1:100$
Area	L^2	$A_r = L_r^2 = 1:10,000$
Volume	L^3	$\forall_r = L_r^3 = 1:1,000,000$
Time	T	$T_r = L_r^{1/2} = 1:10$
Velocity	L/T	$V_r = L_r^{1/2} = 1:10$

* Dimensions are in terms of length and time.
** For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

9. The proposed improvement plans for the model included the use



NOTE: CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD), EL 5686 FT ABOVE MEAN WATER LEVEL AT FATHER POINT, QUEBEC (IGLD 1955)

Figure 3. Model layout

of rubble-mound breakwaters and revetments. Some of the existing breakwaters also are rubble-mound structures. Experience and experimental research have shown that considerable wave energy passes through the interstices of this type structure; thus the transmission and absorption of wave energy became a matter of concern in design of the 1:100-scale model. In small-scale hydraulic models, rubble-mound structures reflect relatively more and absorb or dissipate relatively less wave energy than geometrically similar prototype structures (LeMéhauté 1965). Also, the transmission of wave energy through the breakwater is relatively less for the small-scale model than for the prototype. Consequently, some adjustment in small-scale model rubble-mound structures is needed to ensure satisfactory reproduction of wave-reflection and wave-transmission characteristics. In past investigations at WES (Dai and Jackson 1966, Brasfeild and Ball 1967), this adjustment was made by determining the wave-energy transmission characteristics of the proposed structure in a two-dimensional model using a scale large enough to ensure negligible scale effects. A breakwater section then was developed for the small-scale, three-dimensional model that would provide essentially the same relative transmission of wave energy. Therefore, from previous findings for breakwaters and wave conditions similar to those at Cleveland, it was determined that a close approximation of the correct wave-energy transmission characteristics would be obtained by increasing the size of the rock used in the 1:100-scale model to approximately two times that required for geometric similarity. Accordingly, in constructing the breakwater structures in the Cleveland Harbor and Edgewater Marina model, the rock sizes were computed linearly by scale, then multiplied by 2.0 to determine the actual sizes to be used in the model.

The Model and Appurtenances

10. The model, which was molded in cement mortar, reproduced the west entrance to Cleveland Harbor at the mouth of the Cuyahoga River; approximately 8,800 ft of the harbor shoreline to the east of this entrance, including the westernmost portion of Burke Lakefront Airport;

the entire West Basin; Edgewater Marina; and underwater contours in Lake Erie to an offshore depth of 38 ft with a sloping transition to the wave generator pit elevation of -90 ft. The total area reproduced in the model was approximately 27,400 sq ft, representing about 9.8 square miles in the prototype. A general view of the model is shown in Figure 4 (Edgewater Marina shown in background). Vertical control for model construction was based on low water datum (lwd), el 568.6* ft above mean water level at Father Point, Quebec (International Great Lakes Datum, 1955). Horizontal control was referenced to a local prototype grid system.

11. Model waves were generated by a 120-ft-long wave generator with a trapezoidal-shaped, vertical-motion plunger. The vertical movement of the plunger caused a periodic displacement of water incident to this motion. The length of the stroke and the frequency of the vertical motion were variable over the range necessary to generate waves with the required characteristics. In addition, the wave generator was mounted on retractable casters which enabled it to be positioned to generate waves from the required directions.

12. An Automated Data Acquisition and Control System (ADACS), designed and constructed at WES (Figure 5), was used to secure wave-height data at selected locations in the model. Basically, through the use of a minicomputer, ADACS recorded onto magnetic tape the electrical output of parallel-wire, resistance-type wave gages that measured the change in water-surface elevation with respect to time. The magnetic tape output of ADACS was then analyzed to obtain the wave-height data.

13. A 2-ft (horizontal) solid layer of fiber wave absorber was placed around the inside perimeter of the model to damp any wave energy that might otherwise be reflected from the model walls. In addition, guide vanes were placed along the wave generator sides in the flat pit area to ensure proper formation of the wave train incident to the model contours.

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* All elevations (el) cited herein are in feet referred to low water datum (lwd).

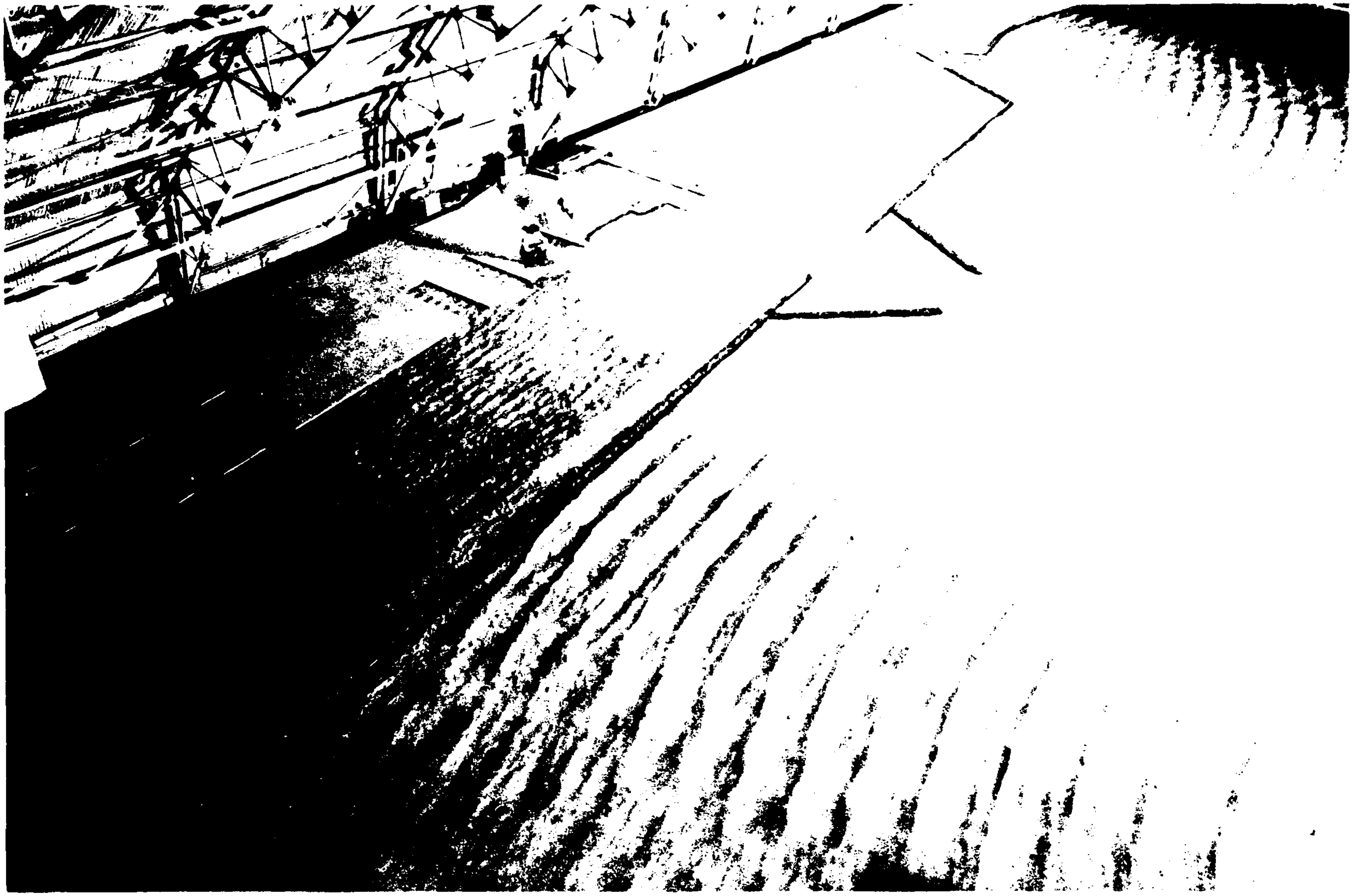

Figure 4. General view of model (Edgewater Marina in background)

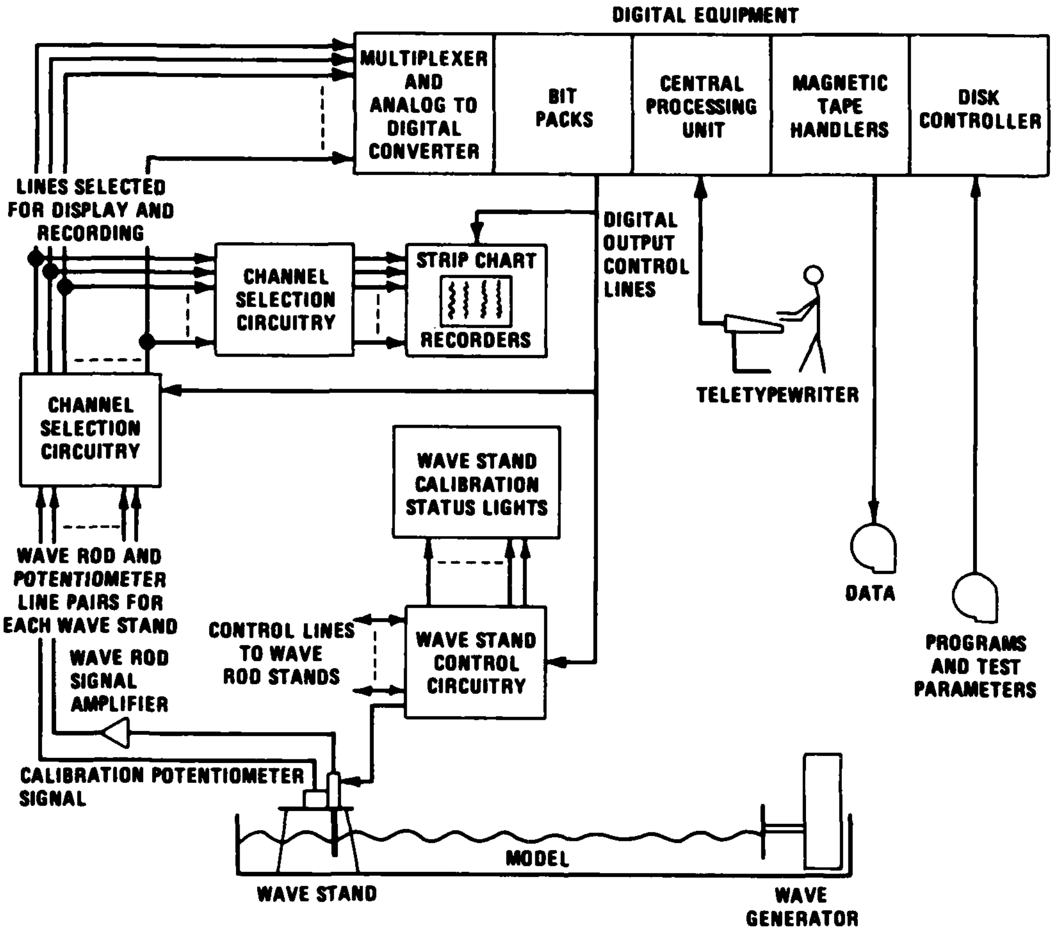

Figure 5. Automated Data Acquisition and Control System (ADACS)

PART III: TEST CONDITIONS AND PROCEDURES

Selection of Test Conditions

14. Still-water levels (swl's) for harbor wave-action models are selected so that the various wave-induced phonomena that are dependent on water depths are accurately reproduced in the model. These phenomena include the refraction of waves in the harbor area, the overtopping of harbor structures by the waves, the reflection of wave energy from harbor structures, and the transmission of wave energy through porous structures.

15. Water levels of the Great Lakes fluctuate from year to year and from month to month. Also, at any given location, the water level can vary from day to day and from hour to hour. Continuous records of the levels of the Great Lakes, tabulated since 1860, indicate that the usual pattern of seasonal variations of water levels consists of highs in summer and lows in late winter. The highest and lowest monthly average levels in Lake Erie usually occur in June and February, respectively. During the period of record (1860-1952), the average lake level of Lake Erie was +1.8 ft for the entire year and +2.1 ft for the ice-free period (April through November). The highest one-month average level of +4.2 ft occurred in May 1952, and the lowest one-month average level of -1.1 ft occurred in February 1936 (Saville 1953). The seasonal variation in the mean monthly level of Lake Erie usually ranges between 1.0 and 2.0 ft, with an average variation of 1.6 ft.

16. Seasonal and longer variations in the levels of the Great Lakes are caused by variations in precipitation and other factors that affect the actual quantities of water in the lakes. Wind tides and seiches are relatively short-period fluctuations caused by the tractive force of wind blowing over the water surface and differential barometric pressures, and are superimposed on the longer period variations in lake level. Large short-period rises in local water level are associated with the most severe storms, which generally occur in the winter when the lake level is usually low; therefore the probability that a high

lake level and large wind tide or seiche will occur simultaneously is relatively small.

17. Lake levels of +4.5 and +5.6 ft were selected by NCB for use during model testing of Edgewater Marina. The +4.5 ft swl represents a 10-year average annual mean level (+3.0 ft) for the boating season (spring, summer, and fall) plus a 1.5-ft short-period peak rise having a recurrence interval of 1 year. The 5.6-ft swl represents a 10-year average annual mean level (+4.1 ft) for the entire year in conjunction with the 1-year peak rise of 1.5 ft.

Factors influencing selection of test wave characteristics

18. In planning the testing program for a model investigation of harbor wave-action problems, it is necessary to select dimensions and directions for the test waves that will allow a realistic test of proposed improvement plans and an accurate evaluation of the elements of the various proposals. Surface-wind waves are generated primarily by the interactions between tangential stresses of wind flowing over water, resonance between the water surface and atmospheric turbulence, and interactions between individual wave components. The height and period of the maximum wave that can be generated by a given storm depend on the wind speed, the length of time that wind of a given speed continues to blow, and the water distance (fetch) over which the wind blows. Selection of test wave conditions entails evaluation of such factors as:

- a. The fetch and decay distances (the latter being the distance over which waves travel after leaving the generating area) for various directions from which waves can attack the problem area.
- b. The frequency of occurrence and duration of storm winds from the different directions.
- c. The alignment, size, and relative geographic position of the navigation entrance to the harbor.
- d. The alignments, lengths, and locations of the various reflecting surfaces inside the harbor.
- e. The refraction of waves caused by differentials in depth in the area lakeward of the harbor, which may create either a concentration or a diffusion of wave energy at the harbor site.

Wave refraction

19. When wind waves move into water of gradually decreasing depth, transformations take place in all wave characteristics except wave period (to the first order of approximation). The most important transformations with respect to the selection of test wave characteristics are the changes in wave height and direction of travel due to the phenomenon referred to as wave refraction. The change in wave height and direction can be determined by plotting refraction diagrams and calculating refraction coefficients. These diagrams are constructed by plotting the position of wave orthogonals (lines drawn perpendicular to wave crests) from deep water into shallow water. If it is assumed that the waves do not break and that there is no lateral flow of energy along the wave crest, the ratio between the wave height in deep water (H_o) and the wave height at any point in shallow water (H) is inversely proportional to the square root of the ratio of the corresponding orthogonal spacings (b_o and b), or $H/H_o = K_s(b_o/b)^{1/2}$. The quantity $(b_o/b)^{1/2}$ is the refraction coefficient, K_r; K_s is the shoaling coefficient. Thus the refraction coefficient multiplied by the shoaling coefficient gives a conversion factor for transfer of deepwater wave heights to shallow-water values. The shoaling coefficient, a function of wavelength and water depth, can be obtained from CERC (1977). For this study, refraction diagrams were prepared for representative wave periods from the critical directions of approach using computer facilities at WES and are detailed in Bottin (1983).

Prototype wave data and selection of test waves

20. Measured prototype wave data on which a comprehensive statistical analysis of wave conditions could be based were unavailable for the Cleveland Harbor area. However, statistical deepwater wave hindcast data representative of this area were obtained from Resio and Vincent (1976) shoreline grid point 10. This publication covers deepwater waves approaching from three angular sectors at the site (Figure 6). Table 1 gives the significant wave heights for all approach angles and seasons combined for recurrence intervals of 5, 10, 20, 50, and 100 years.

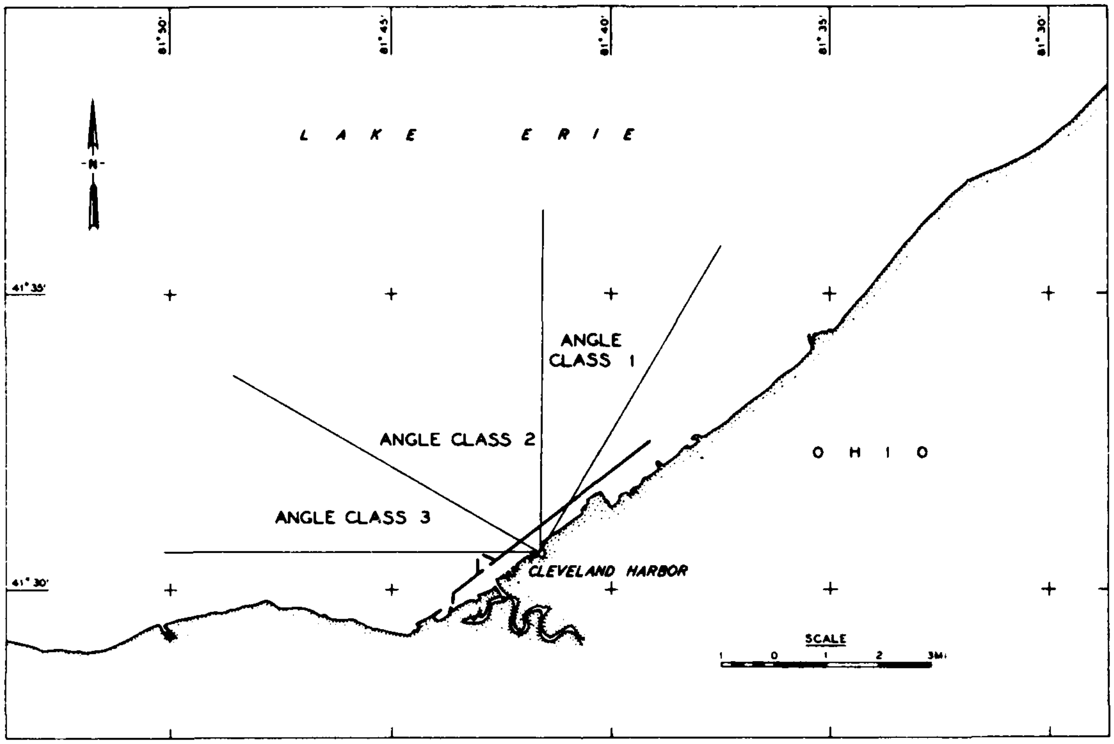

Figure 6. Wave hindcast angle classes

Table 2 shows significant wave period by angle class and wave height. The characteristics of most waves used during model testing were representative of wave conditions occurring during the navigation (boating) season (spring, summer, and fall). In addition, maximum wave heights for the winter season (20-year recurrence interval) were tested to aid in design of the proposed breakwaters. Model test waves were selected from Tables 1 and 2 and converted to shallow-water values by application of refraction and shoaling coefficients as shown in the following tabulation:

Deepwater Direction	Shallow-Water Azimuth, deg	Wave Period sec	Deepwater Wave Height ft	Shallow-Water Wave Height ft	Recurrence Interval years (season)*
West	279	6.0	4.7	3.9	1 (SP)
		7.0	6.9	5.5	5 (SP)
		8.7	11.2	8.1	20 (F)
		9.0**	12.1**	8.6**	20 (W)**
NW and NNW	326	6.2	5.6	5.6	5 (SU)
		7.0	8.2	8.0	20 (SP)
		8.4	11.8	10.7	20 (F)
		8.8**	13.4**	11.9**	20 (W)**
NNE	17	6.0	4.9	4.7	5 (SU)
		7.1	8.2	7.3	20 (SU)
		7.9	10.5	8.9	20 (F)
		8.2**	11.5**	9.8**	20 (W)**

* SU = summer, SP = spring, F = fall, and W = winter seasons.
** Tested with +5.6 ft swl only; others tested with +4.5 ft swl only.

The shallow-water wave directions were taken to be the average directions of the refracted waves for the significant wave periods noted from each deepwater direction.

Analysis of Model Data

21. The relative merits of the various plans tested were evaluated by:

- a. Comparison of wave heights at selected locations in the harbor.
- b. Comparison of wave-induced current patterns and magnitudes.
- c. Visual observations and wave pattern photographs.

In analyzing the wave-height data, the average height of the highest one-third of the waves recorded at each gage location was computed. Computed wave heights then were adjusted to compensate for excessive model wave-height attenuation due to viscous bottom friction by application of Keulegan's equation (Keulegan 1950). From this equation, reduction of wave heights in the model (relative to the prototype) can be calculated as a function of water depth, width of wave front, wave period, water viscosity, and distance of wave travel. Wave-induced current magnitudes were obtained by timing the progress of an injected dye tracer relative to a thin graduated scale placed on the model floor.

PART IV: TESTS AND RESULTS

The Tests

Existing conditions

22. Prior to the conduct of tests of the various improvement plans, comprehensive tests were conducted for existing conditions. Wave-height data were obtained at various locations in the marina (Plate 1) for the test waves listed in paragraph 20. Wave-induced current patterns and magnitudes, wave pattern photographs, and videotape footage were secured for representative test waves from the three test directions.

Improvement plans

23. Model tests were conducted for 24 test plan variations of the three originally proposed marina alternatives. These variations consisted of the installation of new breakwaters and/or harbor entrances, changes in the lengths, crest elevations, and/or cross sections of the existing breakwater structures, and the installation of rubble absorbers along the existing vertical walls in the basin and/or the vertical entrance structures. Wave pattern photographs, videotape footage, and current patterns and magnitudes were obtained for the more promising test plans. Brief descriptions of the improvement plans are presented in the following subparagraphs; dimensional details are presented in Plates 2-14.

a. Plan 1 (Plate 2) consisted of a 125-ft-long sheet-pile structure originating at the spur on the Edgewater breakwater and extending northerly. A 300-ft-long rubble-mound breakwater originated at the northern end of the sheet-pile structure and extended easterly. The crest elevation of these structures was +9.5 ft. In addition, the existing east structure was raised to +9.5 ft (randomly placed rubble).

b. Plan 1A (Plate 2) involved the elements of Plan 1 but rubble was installed (el +12 ft) in the gap of the sheet-pile structure located in the lee of the Edgewater breakwater.

c. Plan 1B (Plate 3) entailed the elements of Plan 1A but an absorber was installed on the lakeward side of the new 125-ft-long sheet-pile structure and the existing spur.

d. Plan 1C (Plate 3) consisted of the elements of Plan 1B with absorber installed along the entire northern wall of the harbor, the harbor and lakeward sides of the curved portion of the Edgewater breakwater, and the western end of the inner structure that protects the boat ramps.

e. Plan 1D (Plate 4) involved the elements of Plan 1C but the entire area between the Edgewater breakwater and the sheet-pile wall was filled with rubble to el +12 ft.

f. Plan 1E (Plate 5) entailed the elements of Plan 1D but the absorber on the harbor side of the curved portion of the Edgewater breakwater was removed. In addition, the absorber at the western end of the inner structure that protects the boat ramps was removed.

g. Plan 1F (Plate 5) included the elements of Plan 1E with the absorber on the lakeward side of the curved portion of the Edgewater breakwater removed.

h. Plan 1G (Plate 5) consisted of the elements of Plan 1E with approximately 550 ft of the absorber removed from along the northern wall (the westernmost portion adjacent to the wider section of the Edgewater breakwater).

i. Plan 1H (Plate 6) entailed the elements of Plan 1G with the absorber removed from the lakeward side of the new 125-ft-long sheet-pile structure and the existing spur.

j. Plan 1I (Plate 6) involved the elements of Plan 1H but the absorber along the northern wall of the harbor adjacent to the sheet-pile structures was removed.

k. Plan 2 (Plate 7) consisted of raising the existing east breakwater to el +9.5 ft (randomly placed rubble), installing rubble absorber from around the spur on the Edgewater breakwater extending southeasterly around the head of the breakwater, and installing rubble absorber along the northern side of the inner breakwater from the head of the structure extending to the opening into Cleveland Harbor.

l. Plan 2A (Plate 7) involved the elements of Plan 2 but the area between the Edgewater breakwater and the sheet-pile wall was filled with rubble to el +12 ft, and rubble absorber was installed along the harbor side of this wall.

m. Plan 2B (Plate 8) entailed the elements of Plan 2A but the absorber along the Cleveland breakwater (south of the entrance into Cleveland Harbor) was removed.

n. Plan 2C (Plate 8) included the elements of Plan 2B but the absorber around the spur on the Edgewater breakwater was removed.

o. Plan 3 (Plate 9) consisted of raising the existing east breakwater to el +9.5 ft (randomly placed rubble) and closing the existing entrance with a structure at el +9.5 ft. A new opening was installed in the Cleveland west breakwater approximately 800 to 1,000 ft north of the junction of the east breakwater. A 200-ft-long rubble-mound structure installed at el +9.5 ft and extending westerly also was included.

p. Plan 3A (Plate 9) included the elements of Plan 3 but rubble was installed (el +12 ft) in the gap of the sheet-pile structure located in the lee of the Edgewater breakwater.

q. Plan 3B (Plate 10) involved the elements of Plan 3 but the entire area between the Edgewater breakwater and the sheet-pile wall was filled with rubble to el +12 ft, and rubble absorber was installed along the harbor side of this wall.

r. Plan 3C (Plate 11) entailed the elements of Plan 3B but the new 200-ft-long rubble-mound structure was reoriented and extended westerly parallel to the east breakwater.

s. Plan 4 (Plate 12) consisted of raising the existing east breakwater to an elevation of approximately +15 ft (two-stone thickness above the existing structure) with randomly placed rubble, replacing the stacked stone on the curved portion of the Edgewater breakwater with randomly placed stone, and installing rubble absorber around the spur on the Edgewater breakwater and along the lakeward side of the inner breakwater. In addition, the entire area between the Edgewater breakwater and the existing sheet-pile wall was filled with rubble to el +12 ft, and rubble absorber was installed along the harbor side of this wall.

t. Plan 4A (Plate 13) entailed the elements of Plan 4 but the western portion of the inner breakwater was removed.

u. Plan 4B (Plate 13) involved the elements of Plan 4A with the absorber removed from the remaining angled portion of the inner breakwater.

v. Plan 4C (Plate 13) included the elements of Plan 4A with the absorber removed only from the northern side of the straight portion of the inner breakwater that extends westerly from the Cleveland breakwater.

w. Plan 4D (Plate 13) entailed the elements of Plan 4C with the absorber removed from around the spur that extends lakeward from the Edgewater breakwater.

x. Plan 4E (Plate 14) consisted of the elements of Plan 4C except the existing sheet-pile wall in the lee of the Edgewater breakwater was removed and that portion of the breakwater was raised to an elevation of approximately +16 ft (one-stone thickness above the existing breakwater). The width of the new crest was approximately 15.5 ft (three-stone thickness) and sloped shoreward on a 1V-on-1.5H slope.

24. The plans listed above are modifications to various alternatives recommended in "Evaluation of Rough Water Problem and Alternative Solutions at Edgewater Marina, Cleveland, Ohio" (Stanley Consultants 1979). The plan numbers in this report do not necessarily coincide with the alternative numbers in the Stanley Consultants' report. Actually, Plans 1-1A in this report consist of modifications to Alternative 2, Option 1; Plans 2-2C and 4-4E entail modifications to Alternative 3; and Plans 3-3B involve modifications to Alternative 1, Option 1, of the Stanley Consultants' report. Plans were tested in this sequence to reduce model construction costs and for ease of model operation.

Wave-height tests

25. Wave-height tests were conducted for the various improvement plans using test waves from one or more of the test directions listed in paragraph 20. Tests involving certain proposed improvement plans were limited to the most critical direction of wave approach (i.e. 326 deg). However, the optimum test plan was tested comprehensively for test waves from 279 and 326 deg. Wave-gage locations for each improvement plan are shown in Plates 2-14.

Wave-induced current pattern and magnitude tests

26. Wave-induced current patterns and magnitudes were determined at selected locations by timing the progress of a dye tracer relative to a known distance on the model floor. These tests were conducted for the optimum improvement plan using test waves from 279 and 326 deg.

Videotape

27. Videotape footage of the Edgewater Marina model was secured for existing conditions and representative improvement plans showing the basin under attack by 8.4-sec, 10.7-ft waves approaching from 326 deg.

This footage was forwarded to NCB for use in briefings, public meetings, etc.

Test Results

28. In evaluating test results, the relative merits of various plans were based on an analysis of measured wave heights and wave-induced current patterns and magnitudes. Model wave heights (significant wave height or $H_{1/3}$) were tabulated to show measured values at selected locations. Wave-induced current patterns and magnitudes were superimposed on wave pattern photographs for the corresponding plan and wave condition tested.

Existing conditions

29. Results of wave-height tests obtained for existing conditions are presented in Table 3. For the boating season (spring, summer, and fall), maximum wavc heights were 3.3 ft in Edgewater Marina (gages 1-4) for 8.4-sec, 10.7-ft waves from 326 deg. For the winter season, maximum wave heights were 6.4 ft in Edgewater Marina for 8.8-sec, 11.9-ft test waves from 326 deg. In most cases, the 326-deg test direction (waves approaching from a direction normal to the Edgewater breakwater) proved to produce the worst wave conditions in the marina.

30. Wave-induced current patterns and magnitudes obtained for existing conditions for representative test waves from all three directions are shown in Photos 1-12. Maximum wave-induced velocities obtained at various locations were as follows:

Location	Max Vel fps	Test Wave	Direction, deg	swl
Area lakeward of breakwater	2.0	9 sec, 8.6 ft	279	+5.6
Outer entrance	5.3	8.8 sec, 11.9 ft	326	+5.6
Inner entrance	4.8	8.8 sec, 11.9 ft	326	+5.6
Entrance to Cleveland Harbor	8.3	8.8 sec, 11.9 ft	326	+5.6
Area inside Edgewater Marina	5.9	8.8 sec, 11.9 ft	326	+5.6

Typical wave patterns for existing conditions also are shown in Photos 1-12.

Improvement plans

31. Wave-height tests conducted for Plans 1-1I for test waves from 326 deg are presented in Table 4. Maximum wave heights obtained in the harbor (gages 1-4) were 3.9, 2.6, 2.7, 1.4, 1.0, 1.0, 1.3, 1.0, 1.0, and 1.2 ft, respectively, for Plans 1-1I. Although Plans 1D, 1E, 1G, and 1H met the established 1.0-ft wave-height criterion, Plan 1H appeared optimum with respect to wave protection and construction costs for the Plan 1 test series. Typical wave patterns for Plans 1 and 1H are shown in Photos 13 and 14.

32. Wave-height measurements obtained for Plans 2-2C for test waves from 326 deg are presented in Table 4. Maximum wave heights obtained in the harbor were 4.4, 0.8, 0.8, and 0.8 ft for Plans 2-2C, respectively. Plans 2A-2C met the established wave-height criterion, and Plan 2C appeared to be optimum with respect to construction costs. Typical wave patterns for Plans 2 and 2C are shown in Photos 15 and 16.

33. Results of wave-height tests with Plans 3-3B installed also are shown in Table 4 for test waves from 326 deg. Maximum wave heights obtained in the harbor for Plans 3-3B were 2.9, 1.9, and 1.0 ft, respectively. Only Plan 3B met the established wave-height criterion. Typical wave patterns secured for Plans 3 and 3B are shown in Photos 17-19.

34. Wave heights secured for Plan 3C for test waves from 279 deg are shown in Table 5. Maximum wave heights in the harbor basin were 0.4 for boating season conditions (well within the established 1.0-ft wave-height criterion). Maximum wave heights obtained in the Cleveland West Basin (gage 10) were 2.0 ft for boating season conditions and 2.1 ft for the winter season for test waves with 20-year recurrence intervals.

35. Wave-height data obtained for Plans 4-4E for test waves from 326 deg are presented in Table 4. Maximum wave heights in the marina were 1.0, 1.0, 1.3, 1.0, 1.2, and 0.9 ft for Plans 4-4E, respectively. Although Plans 4, 4A, 4C, and 4E met the established wave-height

criterion, Plans 4C and 4E appeared to be more promising with respect to wave protection and construction costs.

36. Comprehensive wave-height tests were conducted for Plan 4E for test waves from 279 and 326 deg and are presented in Table 6. Maximum wave heights in the harbor were 0.9 ft or less for wave conditions representing up to a 20-year recurrence interval during the boating season (spring, summer, and fall).

37. Typical wave patterns obtained for Plans 4 and 4E are shown in Photos 20-28. Wave-induced current patterns and magnitudes were obtained for Plan 4E and are superimposed on Photos 21-28. Maximum velocities obtained at various locations were as follows:

Location	Max Vel fps	Test Wave	Direction, deg	swl
Area lakeward of breakwater	3.3	8.8 sec, 11.9 ft	326	+5.6
Outer entrance	3.3	8.8 sec, 11.9 ft	326	+5.6
Inner entrance	3.1	8.8 sec, 11.9 ft	326	+5.6
Entrance to Cleveland Harbor	1.4	8.8 sec, 11.9 ft	326	+5.6
Area inside Edgewater Marina	1.4	8.8 sec, 11.9 ft	326	+5.6

Discussion of test results

38. Test results for existing conditions revealed rough and turbulent wave conditions at Edgewater Marina with wave heights in excess of 13 ft in the entrance and 3 ft in the basin during the boating season (spring, summer, and fall). Significant overtopping of the existing structures and reflections in the entrance and harbor basin were observed. Due to this overtopping, wave-induced current magnitudes up to 5 fps in the basin and almost 4 fps in the entrance were measured for boating season conditions.

39. Test results obtained with the new breakwater installed at the existing entrance, the east breakwater raised to an elevation of +9.5 ft, and various absorber modifications (Plan 1-1I) indicated that several of the plans (Plans 1D, 1E, 1G, and 1H) would provide the required wave protection in the marina. Plan 1H, however, required less

volume of absorber stone, as opposed to the other plans that met the established wave-height criterion and, therefore, appeared to be optimal for the Plan 1 test series.

40. Wave-height measurements obtained with absorbers installed adjacent to the various entrance structures and the east breakwater raised to an elevation of +9.5 ft (Plans 2-2C) revealed that Plans 2A-2C would provide adequate wave protection in the basin. Plan 2C, however, requiring less volume of stone, appeared to be optimal for the Plan 2 test series.

41. Test results with the existing entrance closed, the east breakwater raised to an elevation of +9.5 ft, and a new entrance installed through the Cleveland Harbor west breakwater (Plans 3-3B) indicated that only Plan 3B would meet the established wave-height criterion of 1.0 ft in the marina for test waves from 326 deg. Although Plan 3C was not subjected to test waves from 326 deg, wave heights in the basin should be comparable to those obtained for Plan 3B since only a minor change in orientation of the new breakwater occurred. A comparison of wave heights for existing conditions and Plan 3C for test waves from 279 deg indicated that wave heights in the Cleveland Harbor West Basin would increase significantly due to the wave energy penetrating the new opening.

42. Evaluation of test results with the curved portion of the Edgewater breakwater replaced with randomly placed stone, the east breakwater raised to an elevation of +15 ft, and absorbers installed adjacent to various entrance structures (Plans 4-4E) indicated that several of the plans (Plans 4, 4A, 4C, and 4E) met the required wave-height criterion. Considering the wave protection provided and the volume of stone required, however, it appeared that Plans 4C and 4E were optimum. Plan 4C involved increasing the width while Plan 4E entailed raising the crest elevation of the Edgewater breakwater.

43. It should be noted that every plan tested which met the established wave-height criterion in the marina required modification of the Edgewater breakwater (that portion adjacent to the existing sheet-pile wall). This portion of the breakwater was either raised or

increased in width to prevent excessive overtopping that resulted in excessive wave heights in the marina.

44. Evaluation of comprehensive tests with Plan 4E installed in the model for waves from 279 and 326 deg indicated that maximum wave heights in the harbor would not exceed 0.9 ft in the marina during the boating season for conditions occurring up to a 20-year recurrence interval. Maximum wave-induced current velocities obtained were 3 fps in the entrance and 1 fps in the basin during the boating season. For smaller everyday waves, circulation in the basin may be essentially non-existent, and consideration may be given to artificial methods to improve water quality.

45. Although only Plan 4E was tested comprehensively in the model, each plan meeting the wave-height criterion (reducing wave heights to 1.0 ft or less) for each test series should yield comparable results. For each condition, wave energy was prevented from entering the harbor for the most severe incident test waves (8.4-sec, 10.7-ft waves from 326 deg) occurring during the boating season. Since wave energy entering the basin was reduced by these improvement plans, hazardous current conditions also should be reduced or eliminated.

PART V: CONCLUSIONS

46. Based on the results of the hydraulic model investigation reported herein, it was concluded that:

a. For existing conditions, rough and turbulent wave and current conditions existed in the harbor entrance and basin during periods of storm wave attack.

b. Of the improvement plans tested with the new breakwater installed at the existing entrance and the east breakwater raised to an elevation of +9.5 ft (Plans 1-1I), Plan 1H appeared to be optimal with respect to wave protection and construction costs.

c. Of the improvement plans tested with absorber installed adjacent to the entrance structures and the east breakwater raised to an elevation of +9.5 ft (Plans 2-2C), Plan 2C appeared to be optimal with respect to wave protection and construction costs.

d. Of the improvement plans tested with the existing entrance closed and raised to an elevation of +9.5 ft, the east breakwater raised to an elevation of +9.5 ft, and a new entrance installed through the Cleveland Harbor west breakwater (Plans 3-3C), Plans 3B and 3C appeared to be optimal with respect to wave protection in the marina, however, wave heights in the Cleveland Harbor West Basin increased significantly.

e. Of the improvement plans tested with the curved portion of the Edgewater breakwater replaced with randomly placed stone and the east breakwater raised to an elevation of +15 ft (Plans 4-4E), Plans 4C and 4E appeared to be optimum with respect to wave protection afforded and construction costs.

f. For any improvement plan to be effective (i.e., wave heights reduced to 1.0 ft or less in the marina) a portion of the existing Edgewater breakwater (that portion adjacent to the existing sheet-pile wall) will have to be either raised or increased in width.

g. The installation of any of the optimal improvement plans tested should reduce or eliminate hazardous wave-induced currents in the basin during the boating season (spring, summer, and fall).

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Table 1

Wave Heights for All Approach Angles and Seasons

Recurrence Interval, year	Wave Height, ft		
	Angle Class 1	Angle Class 2	Angle Class 3
	Winter		
5	8.2	11.2	10.8
10	10.2	12.1	11.5
20	11.5	13.4	12.1
50	13.8	14.8	13.1
100	15.1	15.7	13.8
	Spring		
5	3.9	5.2	6.9
10	4.9	6.6	7.9
20	6.2	7.5	8.9
50	7.5	9.2	10.2
100	8.5	10.2	11.2
	Summer		
5	4.9	5.6	6.2
10	5.9	6.2	7.2
20	7.5	7.2	8.2
50	10.2	8.5	9.5
100	12.1	9.2	10.5
	Fall		
5	8.9	9.5	9.8
10	9.8	10.8	10.5
20	10.5	11.8	11.2
50	11.5	13.1	12.1
100	12.1	14.4	12.8

Table 2

Significant Period, sec, by Angle Class and Wave Height

Wave Height ft	Angle Class 1	Angle Class 2	Angle Class 3
1	2.5	2.4	2.5
2	3.8	3.8	3.9
3	4.7	4.7	4.9
4	5.4	5.3	5.6
5	6.0	5.9	6.1
6	6.3	6.3	6.5
7	6.7	6.6	6.9
8	7.0	6.9	7.4
9	7.4	7.3	7.8
10	7.7	7.6	8.2
11	8.0	8.0	8.6
12	8.4	8.4	9.0
13	8.7	8.7	9.5
14	9.1	9.0	9.9
15	9.4	9.4	10.3
16	9.7	9.8	10.7
17	10.1	10.1	11.1
18	10.4	10.5	11.6
19	10.8	10.8	12.0
20	11.1	11.1	12.4
21	11.4	11.5	12.8
22	11.8	11.9	13.2
23	12.1	12.2	13.7
24	12.5	12.6	14.1
25	12.8	12.9	14.5

Table 3

Wave Heights for Existing Conditions

Test Wave			Wave Height, ft									
Direction deg	Period sec	Height ft	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
						+4.5 ft swl						
279	6.0	3.9	0.3	0.4	0.1	0.7	0.1	0.9	3.1	3.0	3.8	0.3
	7.0	5.5	0.4	0.7	0.5	1.4	0.3	2.2	2.0	4.0	4.9	0.4
	8.7	8.1	1.1	1.7	1.7	2.2	2.1	3.0	9.4	6.4	4.9	0.7
326	6.2	5.6	0.4	1.1	0.4	1.7	0.5	1.8	4.5	6.2	4.8	0.4
	7.0	8.0	0.8	2.1	1.2	2.3	2.1	3.8	7.5	10.4	5.9	1.7
	8.4	10.7	2.9	2.9	2.2	3.3	3.8	6.5	7.0	13.4	7.6	1.8
17	6.0	4.7	<0.1	0.1	<0.1	0.1	<0.1	0.1	0.4	0.6	1.0	0.3
	7.1	7.3	0.2	0.6	0.4	0.6	0.3	0.8	1.3	4.6	1.9	1.2
	7.9	8.9	0.4	1.0	0.7	1.0	0.8	2.1	3.7	7.9	2.1	0.8
						+5.6 ft swl						
279	9.0	8.6	2.2	2.9	1.8	3.6	5.9	3.3	6.7	5.8	4.8	1.7
326	8.8	11.9	4.6	6.4	3.6	5.3	3.8	4.9	5.0	15.2	7.9	3.9
17	8.2	9.8	2.1	1.4	1.1	2.3	1.4	3.7	4.0	7.9	1.3	0.9

Table 4

Wave Heights for Plans 1-1I, 2-2C, 3-3B, and 4-4E for 8.4-sec, 10.7-ft Test Waves from 326 deg, +4.5 ft swl

Plan No.	Wave Height, ft Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
1	1.1	2.3	1.4	3.9	1.6	3.7	3.0	8.3	8.2	1.9
1A	1.1	1.9	1.4	2.6	1.0	3.0	3.5	7.5	8.4	1.8
1B	1.2	1.3	1.1	2.7	1.0	3.0	3.7	7.0	7.6	1.5
1C	1.0	0.8	0.7	1.4	0.6	1.6	3.2	6.5	7.4	1.5
1D	0.9	0.8	0.7	1.0	0.5	1.2	3.1	6.3	7.7	1.6
1E	0.9	0.7	0.7	1.0	0.6	2.3	3.0	6.7	7.5	1.4
1F	0.9	0.8	0.7	1.3	0.6	2.7	3.2	7.0	7.6	1.4
1G	1.0	0.8	1.0	1.0	0.6	2.2	3.1	6.4	7.5	1.2
1H	0.9	0.8	1.0	1.0	0.6	2.0	3.3	6.3	7.4	1.3
1I	1.1	0.9	1.2	1.2	0.8	1.9	2.9	7.1	7.8	1.4
2	1.5	2.2	1.0	4.4	1.5	1.9	4.2	8.4	8.0	1.6
2A	0.7	0.5	0.7	0.8	0.4	1.8	3.4	8.2	7.9	1.4
2B	0.6	0.5	0.8	0.8	0.4	1.8	3.8	8.7	8.2	1.5
2C	0.6	0.5	0.7	0.8	0.4	1.7	3.7	8.6	7.9	1.4
3	1.7	1.8	1.3	2.9	1.0	2.7	4.2	2.9	4.9	1.9
3A	1.2	1.6	1.2	1.9	0.9	2.3	4.0	2.8	4.7	1.8
3B	0.9	0.8	0.9	1.0	0.6	1.6	3.4	2.8	4.7	1.8
4	1.0	0.9	0.8	1.0	0.6	1.3	2.6	6.9	0.3	1.7
4A	0.9	1.0	0.8	1.0	1.0	1.4	2.3	7.1	0.4	1.8
4B	1.0	1.1	0.8	1.3	1.4	1.5	2.1	6.8	0.5	1.7
4C	1.0	0.8	0.7	1.0	0.9	1.3	2.9	6.2	0.5	1.5
4D	1.0	0.9	0.7	1.2	1.1	1.2	3.5	5.4	0.6	1.5
4E	0.6	0.6	0.7	0.9	1.0	1.1	2.7	4.8	0.5	1.5

Table 5

Wave Heights for Plan 3C for Test Waves from 279 deg

Test Wave		Wave Height, ft									
Period sec	Height ft	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
					+4.5 ft swl						
6.0	3.9	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.3	0.4	1.2	0.8
7.0	5.5	0.1	0.1	0.1	<0.1	<0.1	0.4	0.3	0.5	3.2	1.2
8.7	8.1	0.3	0.2	0.1	0.4	0.1	0.3	1.4	1.4	3.9	2.0
					+5.6 ft swl						
9.0	8.6	0.2	0.4	0.2	0.4	0.3	0.5	1.4	2.5	4.3	2.1

Table 6

Wave Heights for Plan 4E for Test Waves from 279 and 326 deg

Test Wave			Wave Height, ft									
Direction deg	Period sec	Height ft	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
						+4.5 ft swl						
279	6.0	3.9	0.1	0.1	0.1	0.1	0.2	0.4	0.6	1.5	0.2	0.2
	7.0	5.5	0.3	0.1	0.1	0.2	0.1	0.5	0.4	2.6	0.1	0.3
	8.7	8.1	0.2	0.3	0.3	0.5	0.7	0.2	2.4	4.1	0.2	0.7
326	6.2	5.6	0.1	0.2	0.1	0.1	0.1	0.5	1.1	1.2	0.2	0.3
	7.0	8.0	0.6	0.3	0.6	0.4	0.5	1.2	1.2	3.1	0.5	0.7
	8.4	10.7	0.6	0.6	0.7	0.9	1.0	1.1	2.7	4.8	0.5	1.5
						+5.6 ft swl						
279	9.0	8.6	0.4	0.7	0.5	0.6	0.9	0.4	2.1	3.8	0.3	0.8
326	8.8	11.9	0.8	1.1	1.4	0.7	1.0	1.4	3.0	5.9	0.6	2.5

Photo 1. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6-sec, 3.9-ft waves from 279 deg; +4.5 ft swl

Photo 2. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 7-sec, 5.5-ft waves from 279 deg; +4.5 ft swl

Photo 3. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 8.7-sec, 8.1-ft waves from 279 deg; +4.5 ft swl

Photo 4. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 9-sec, 8.6-ft waves from 279 deg; +5.6 ft swl

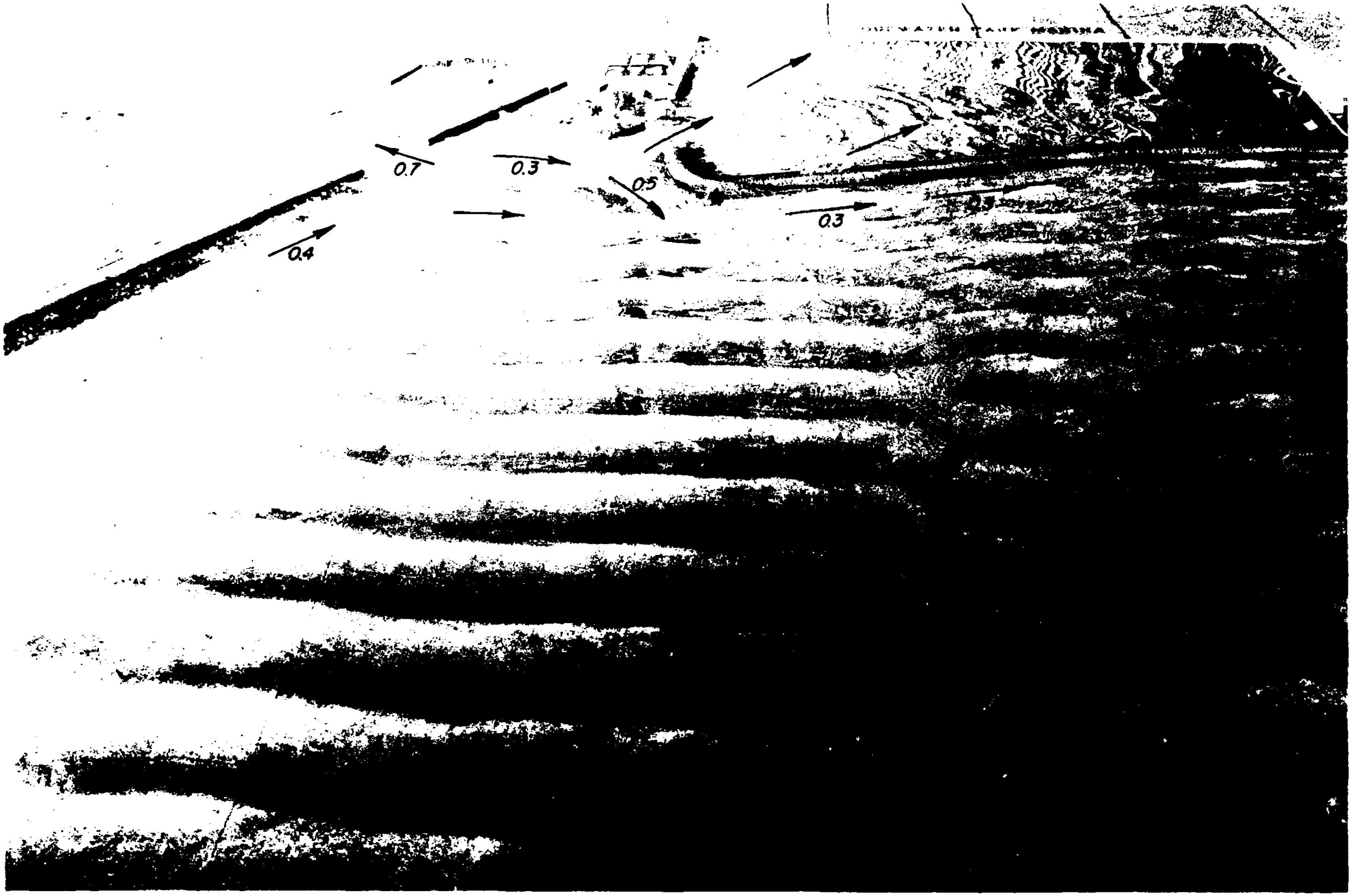


Photo 5. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6.2-sec, 5.6-ft waves from 326 deg; +4.5 ft swl

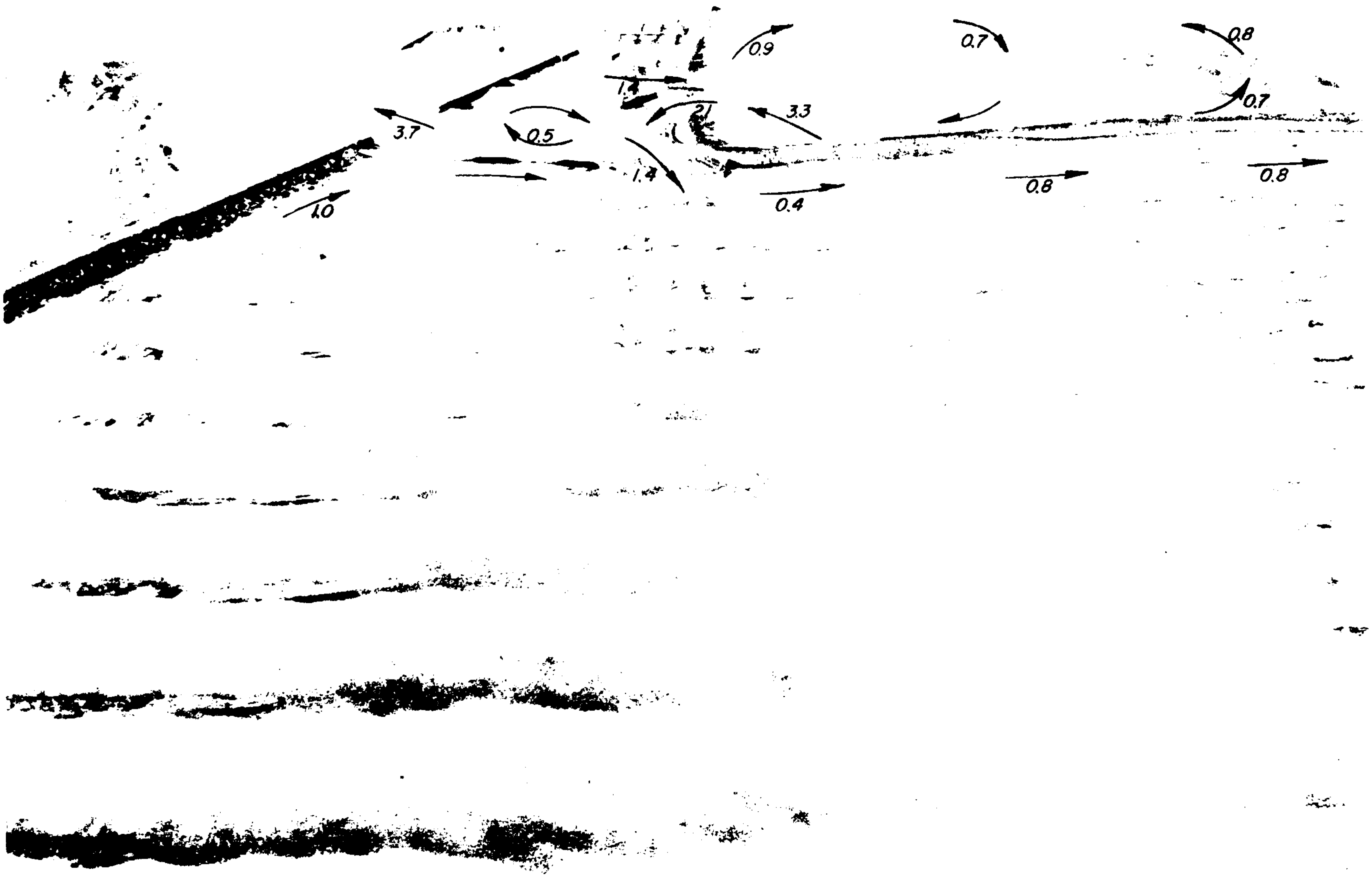


Photo 6. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 7-sec, 8-ft waves from 326 deg; +4.5 ft swl

Photo 7. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 8.4-sec, 10.7-ft waves from 326 deg; +4.5 ft swl

Photo 8. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 8.8-sec, 11.9-ft waves from 326 deg; +5.6 ft swl

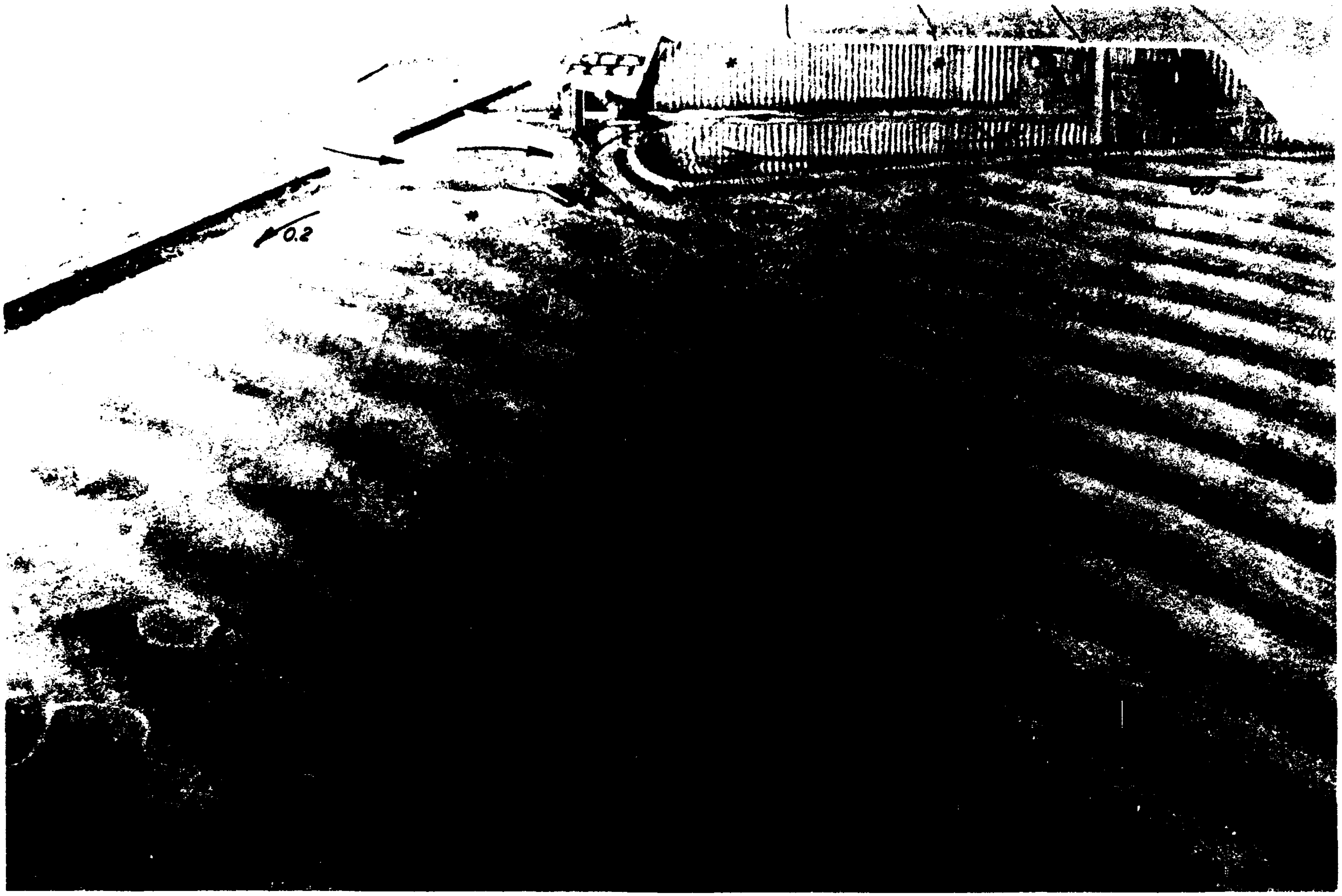


Photo 9. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6-sec, 4.7-ft waves from 17 deg; +4.5 ft swl

Photo 10. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 7.1-sec, 7.3-ft waves from 17 deg; +4.5 ft swl

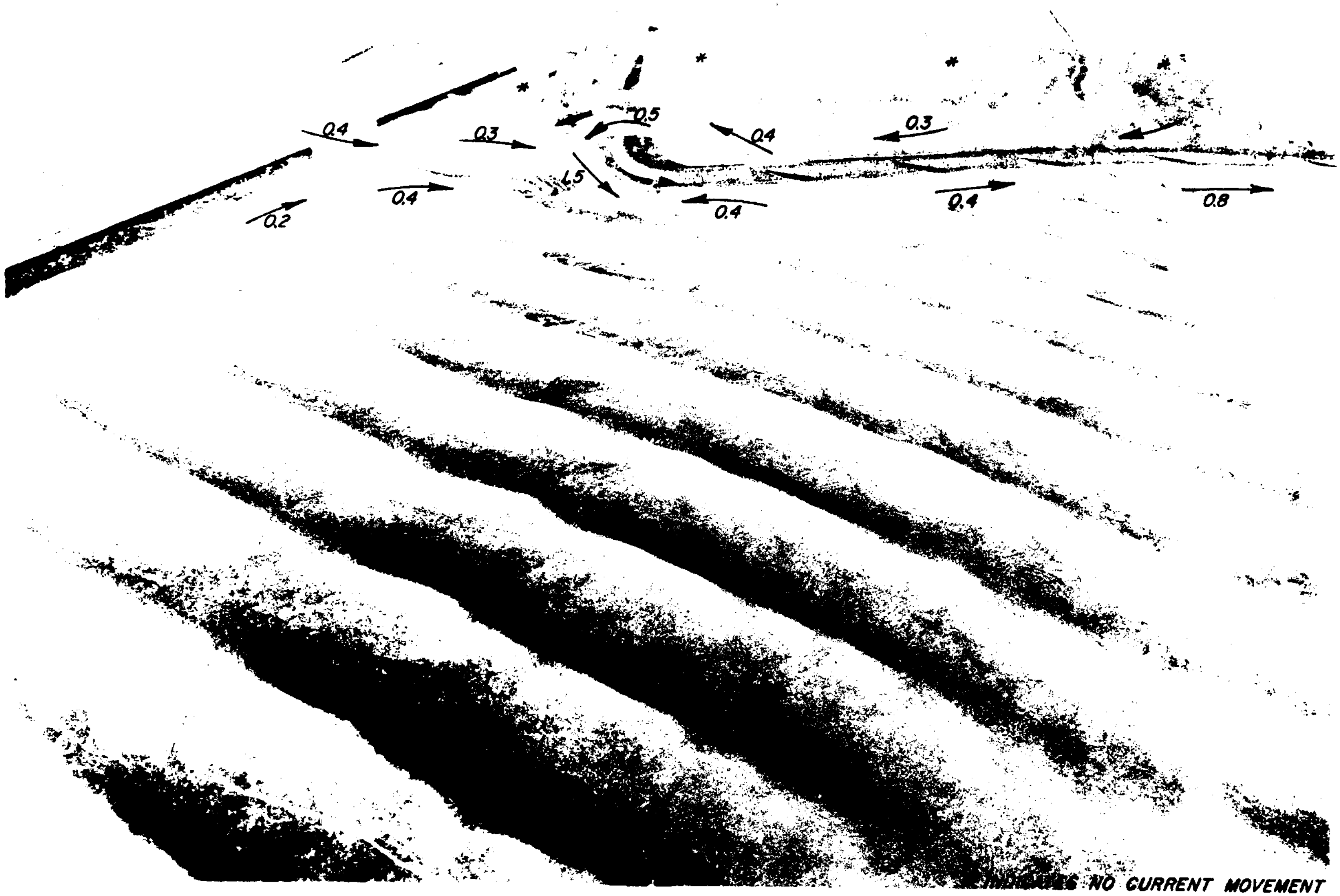


Photo 11. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 7.9-sec, 8.9-ft waves from 17 deg; +4.5 ft swl

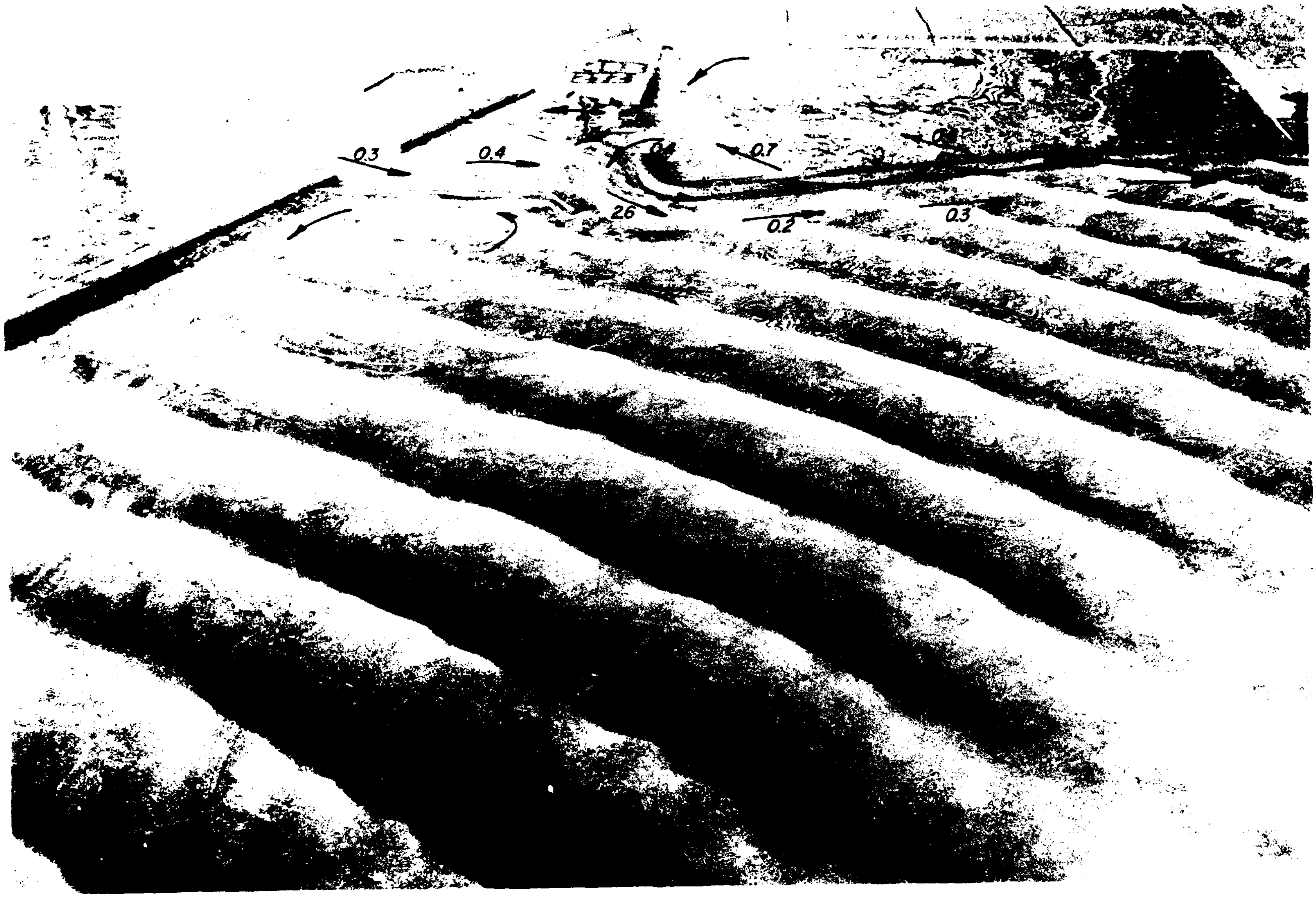


Photo 12. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 8.2-sec, 9.8-ft waves from 17 deg; +5.6 ft swl

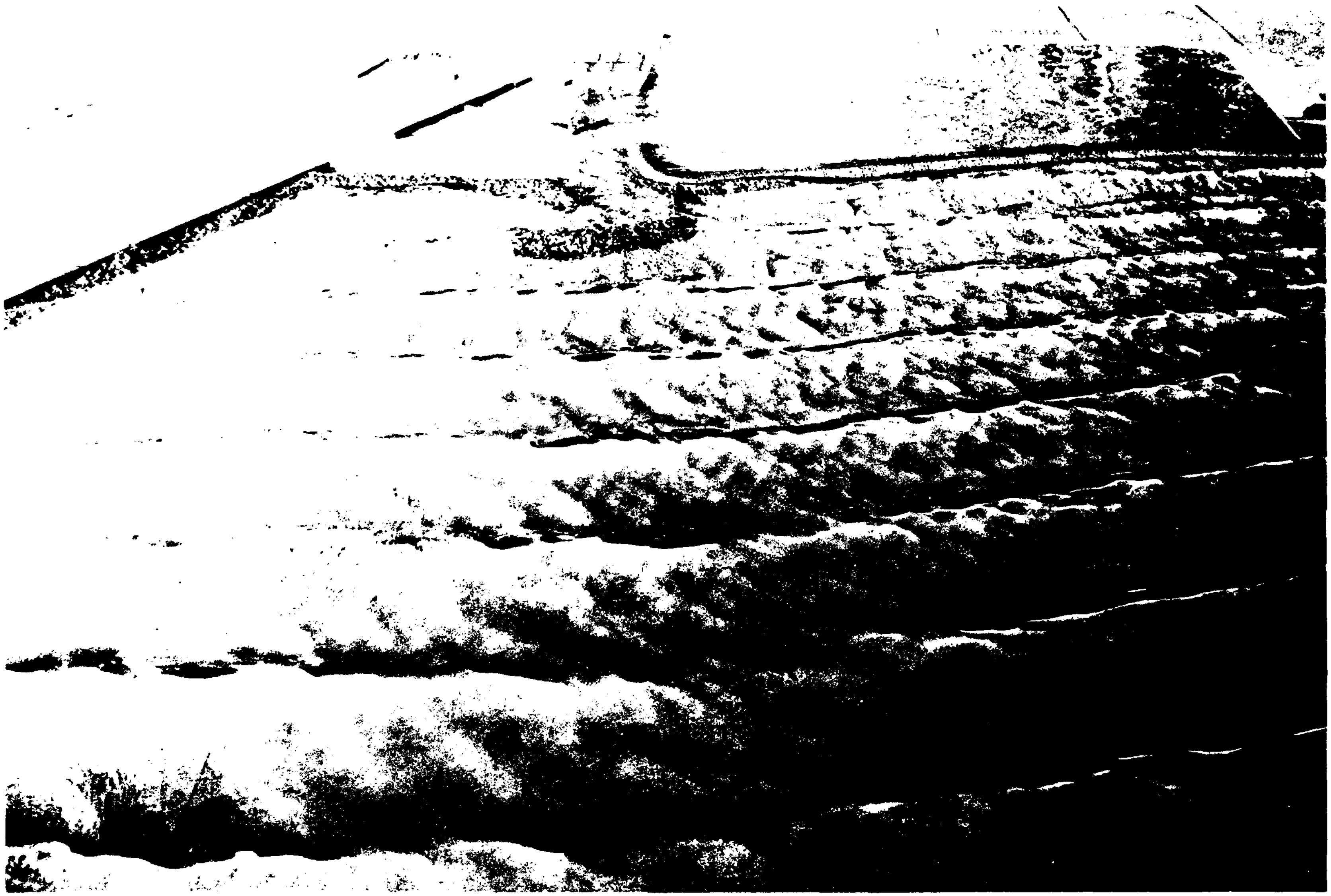


Photo 13. Typical wave patterns for Plan 1, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 14. Typical wave patterns for Plan 1H, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 15. Typical wave patterns for Plan 2, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 16. Typical wave patterns for Plan 2C, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 17. Typical wave patterns for Plan 3, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 18. Typical wave patterns for Plan 3B, 8.4-sec, 10.7-sec waves from 326 deg; +4.5 ft swl

Photo 19. Typical wave patterns in the western portion of Cleveland Harbor and at the new Plan 3B entrance: 8.4-sec, 10.7-ft waves from 326 deg; +4.5 ft swl

Photo 20. Typical wave patterns for Plan 4; 8.4-sec, 10.7-ft waves from 326 deg; +4.5 ft swl

Photo 21. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 6-sec, 3.9-ft waves from 279 deg; +4.5 ft swl

Photo 22. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 6-sec, 5.5-ft waves from 279 deg; +4.5 ft swl

Photo 23. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 8.7-sec, 8.1-ft waves from 279 deg; +4.5 ft swl

Photo 24. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 9-sec, 8.6-ft waves from 279 deg; +5.6 ft swl

Photo 25. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 6.2-sec, 5.6-ft waves from 326 deg; +4.5 ft swl

Photo 26. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 7-sec, 8-ft waves from 326 deg; +4.5 ft swl

Photo 27. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 8.4-sec, 10.7-ft waves from 326 deg; +4.5 ft swl

Photo 28. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 4E; 8.8-sec, 11.9-ft waves from 326 deg; +5.6 ft swl

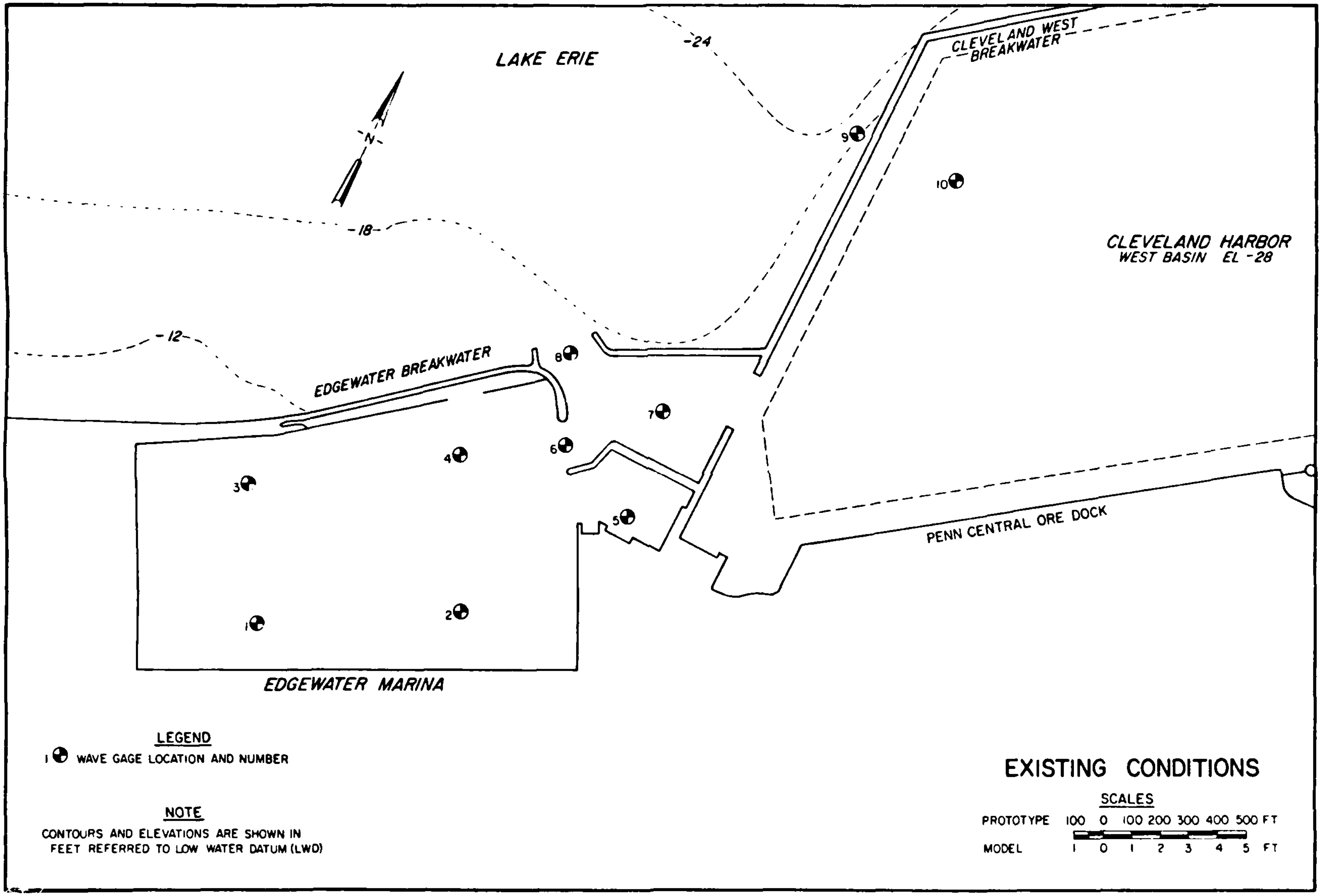

LAKE ERIE
N
-24
-18
-12
CLEVELAND WEST BREAKWATER
CLEVELAND HARBOR
WEST BASIN EL -28
EDGEWATER BREAKWATER
PENN CENTRAL ORE DOCK
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
EXISTING CONDITIONS
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT

PLATE 1

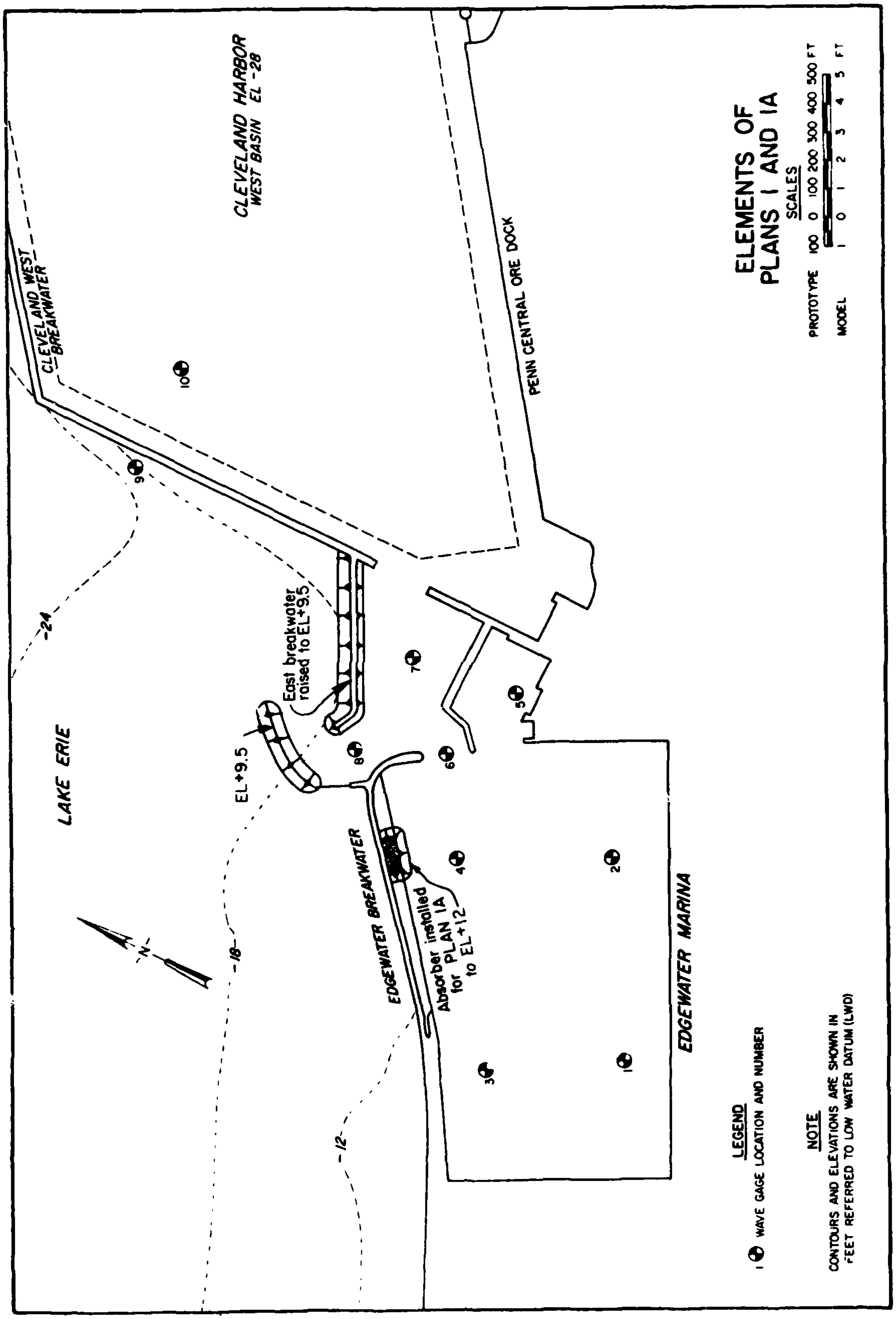
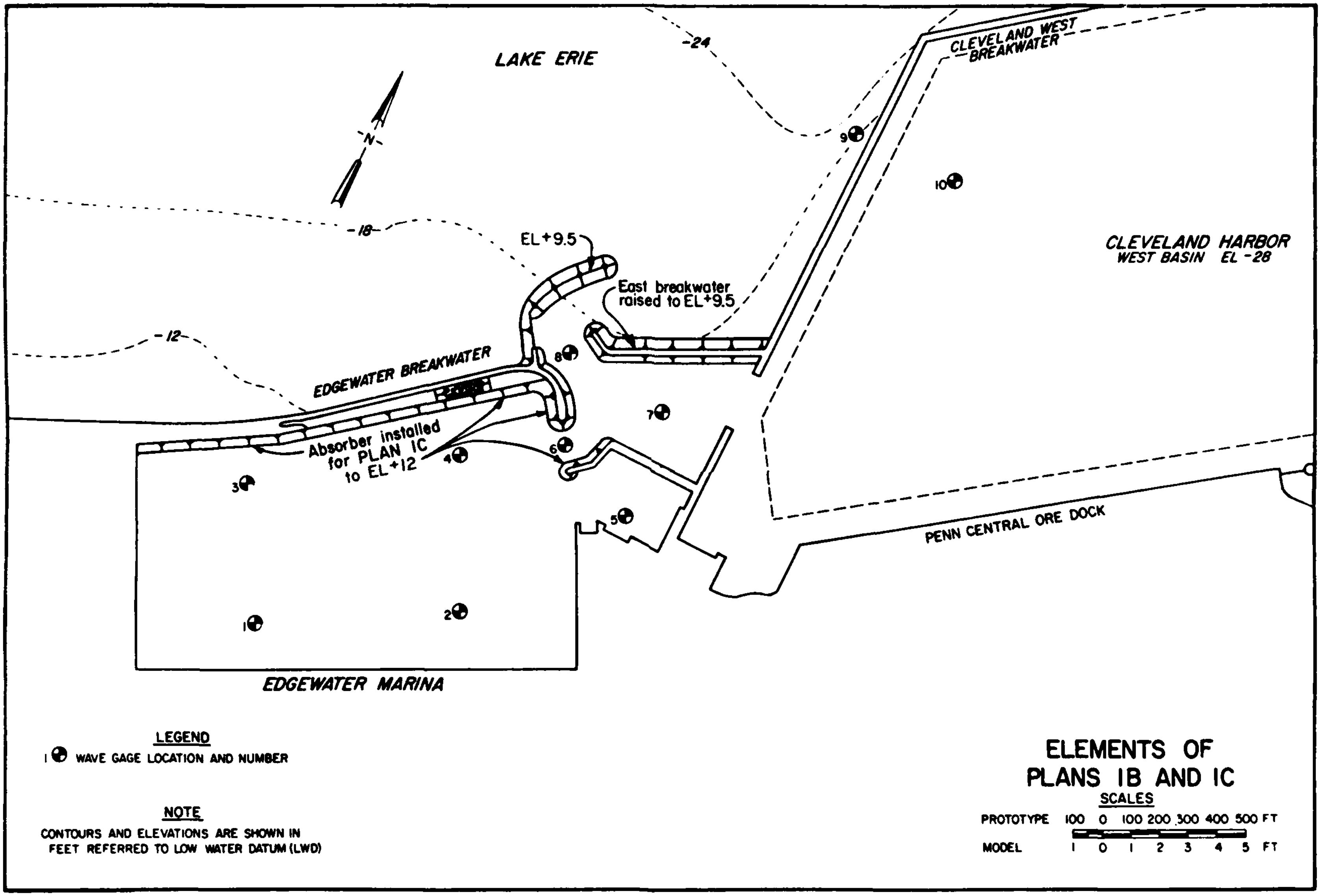
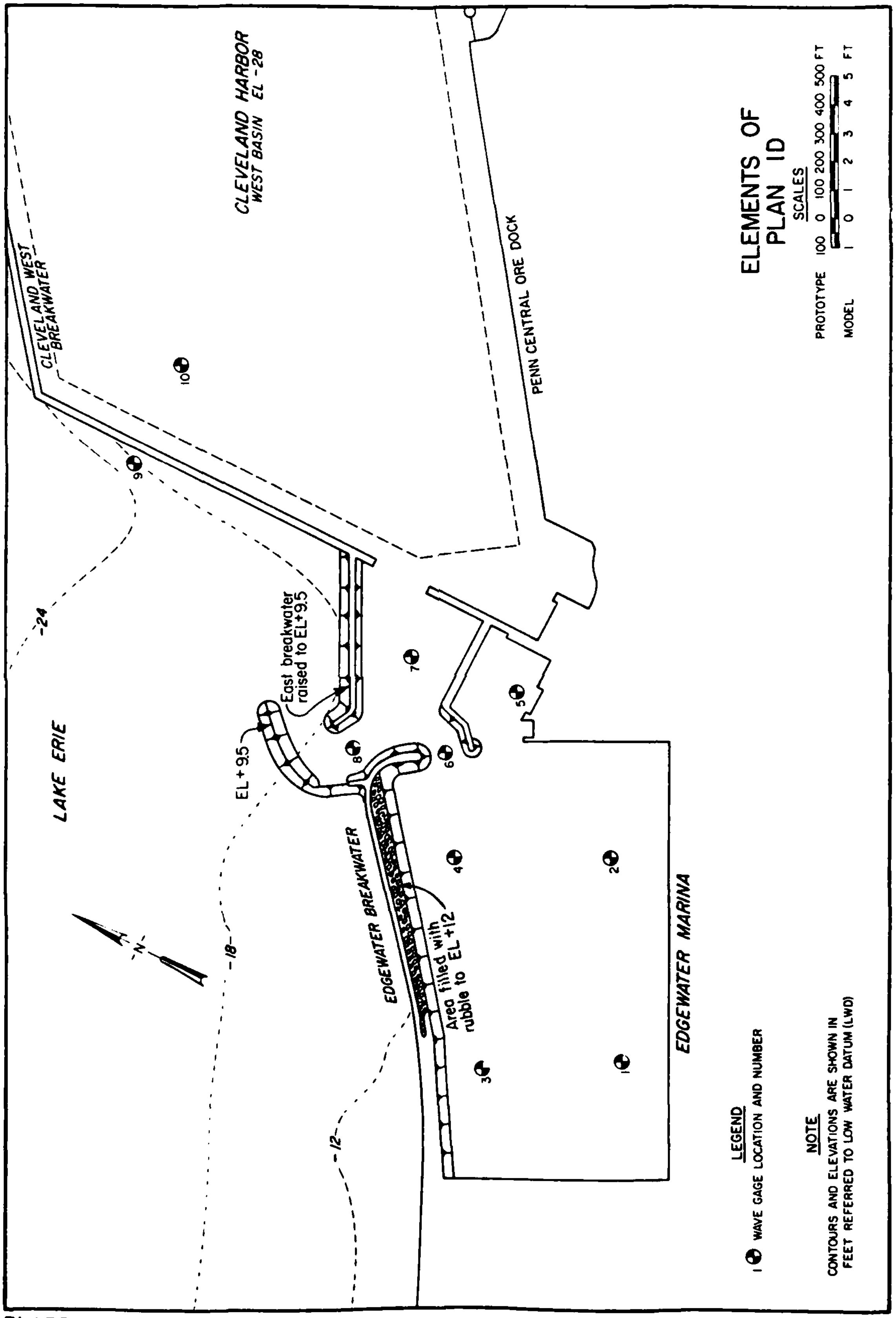

ELEMENTS OF PLANS I AND IA
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
East breakwater raised to EL+9.5
EL+9.5
LAKE ERIE
EDGEWATER BREAKWATER
Absorber installed for PLAN IA to EL+12
EDGEWATER MARINA
N
-24
-18
-12
1
2
3
4
5
6
7
8
9
10
LEGEND
WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)

PLATE 2

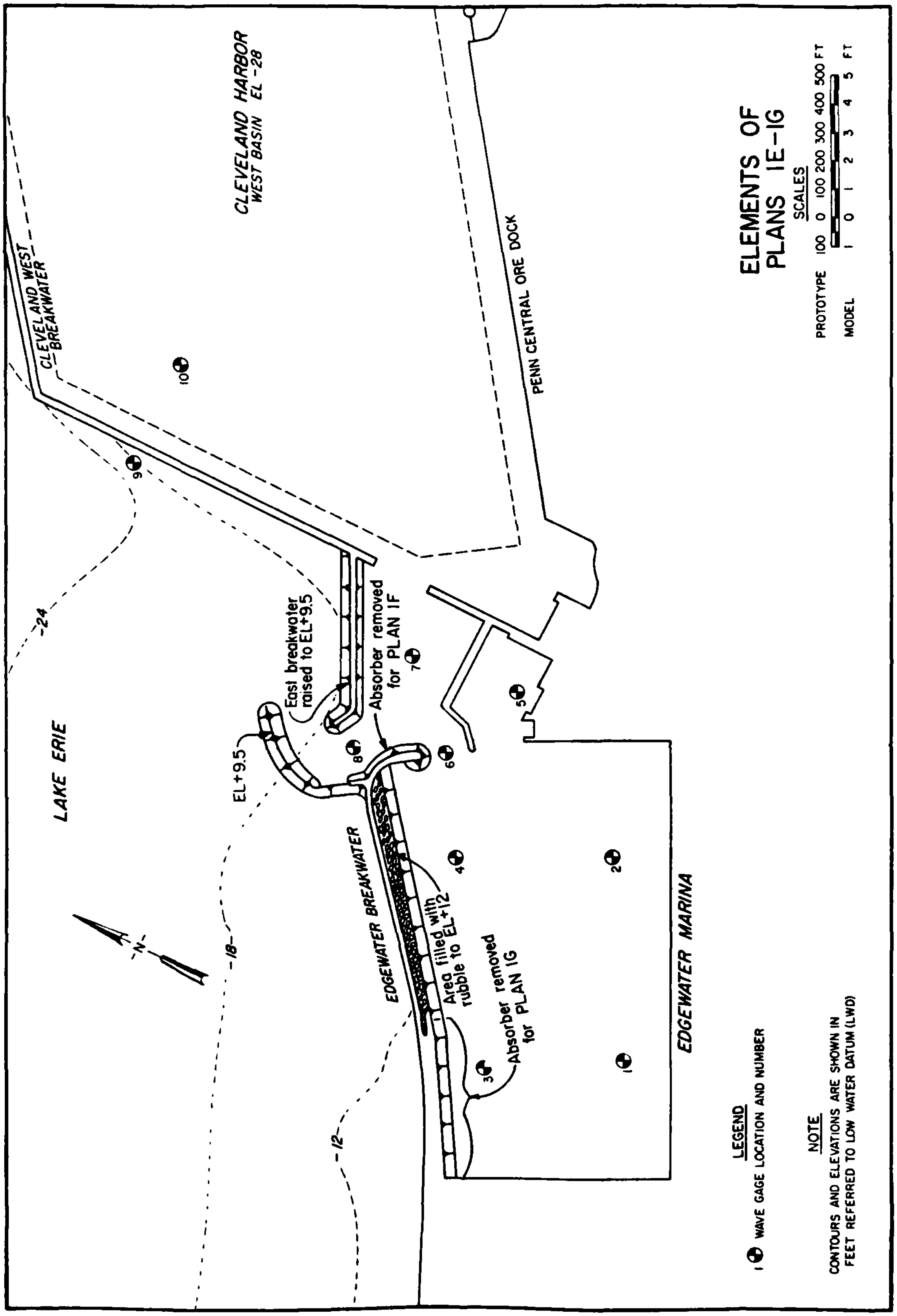


ELEMENTS OF PLANS IB AND IC



ELEMENTS OF
PLAN 1D
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
LAKE ERIE
East breakwater raised to EL+9.5
EL+9.5
EDGEWATER BREAKWATER
Area filled with rubble to EL+12
EDGEWATER MARINA
N
-24
-18
-12
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)

PLATE 4



CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
ELEMENTS OF PLANS 1E-1G
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
LAKE ERIE
-24
-18
-12
EL+9.5
East breakwater raised to EL+9.5
Absorber removed for PLAN 1F
EDGEWATER BREAKWATER
Area filled with rubble to EL+12
Absorber removed for PLAN 1G
EDGEWATER MARINA
N
1
2
3
4
5
6
7
8
9
10
LEGEND
WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)

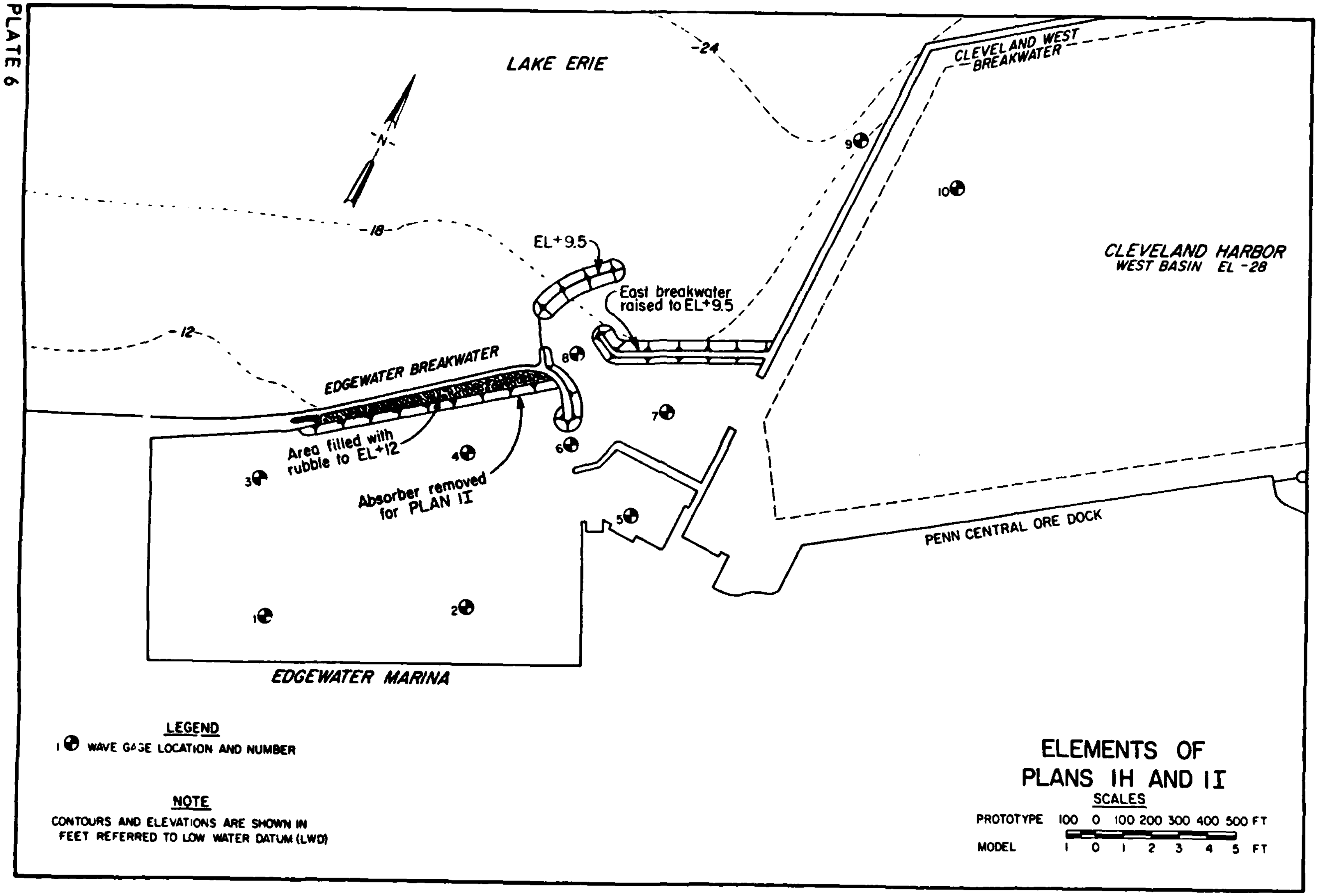

LAKE ERIE
-24
-18
-12
N
CLEVELAND AND WEST BREAKWATER
CLEVELAND HARBOR
WEST BASIN EL -28
EL+9.5
East breakwater raised to EL+9.5
EDGEWATER BREAKWATER
Area filled with rubble to EL+12
Absorber removed for PLAN II
PENN CENTRAL ORE DOCK
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
ELEMENTS OF PLANS IH AND II
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT

PLATE 6

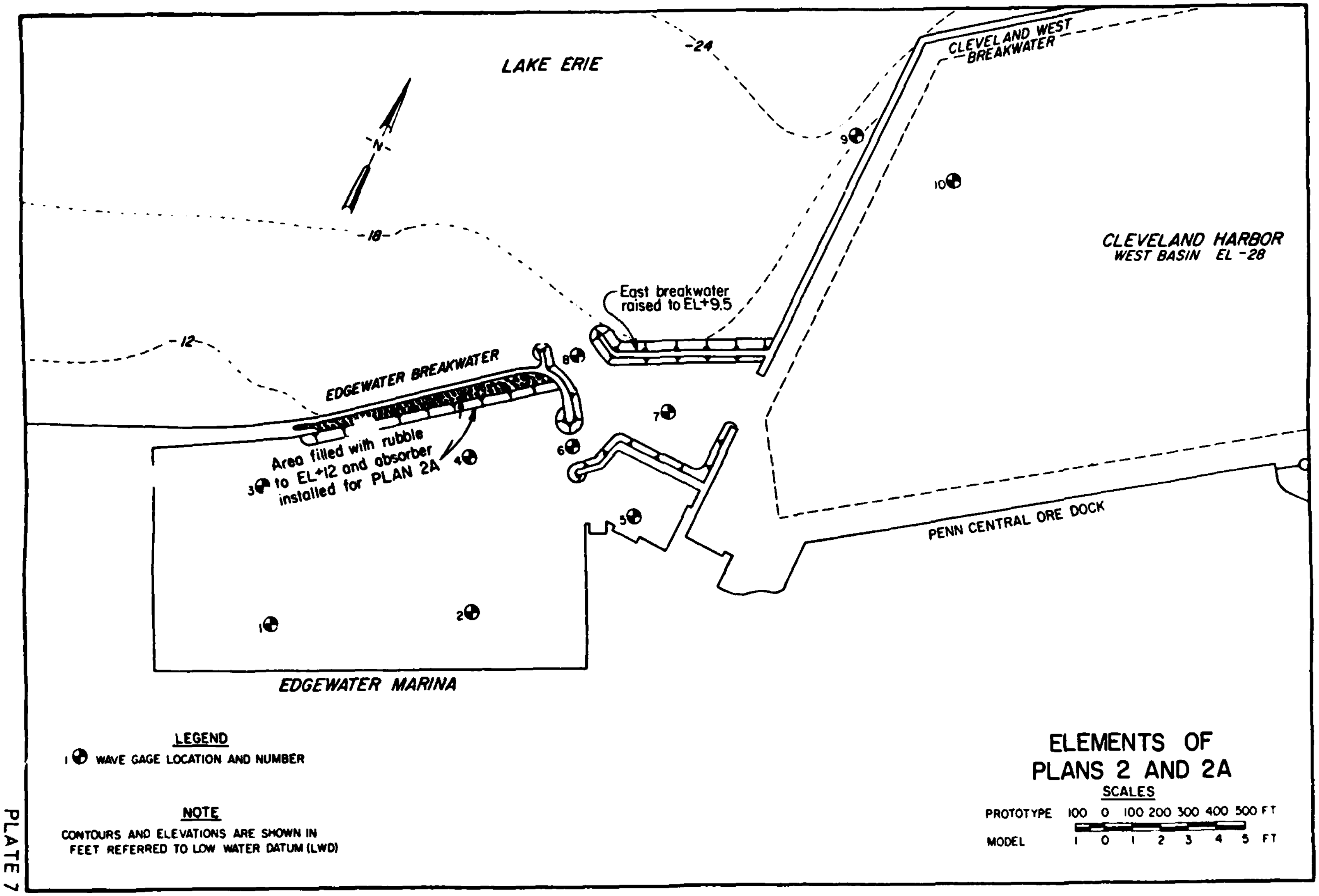
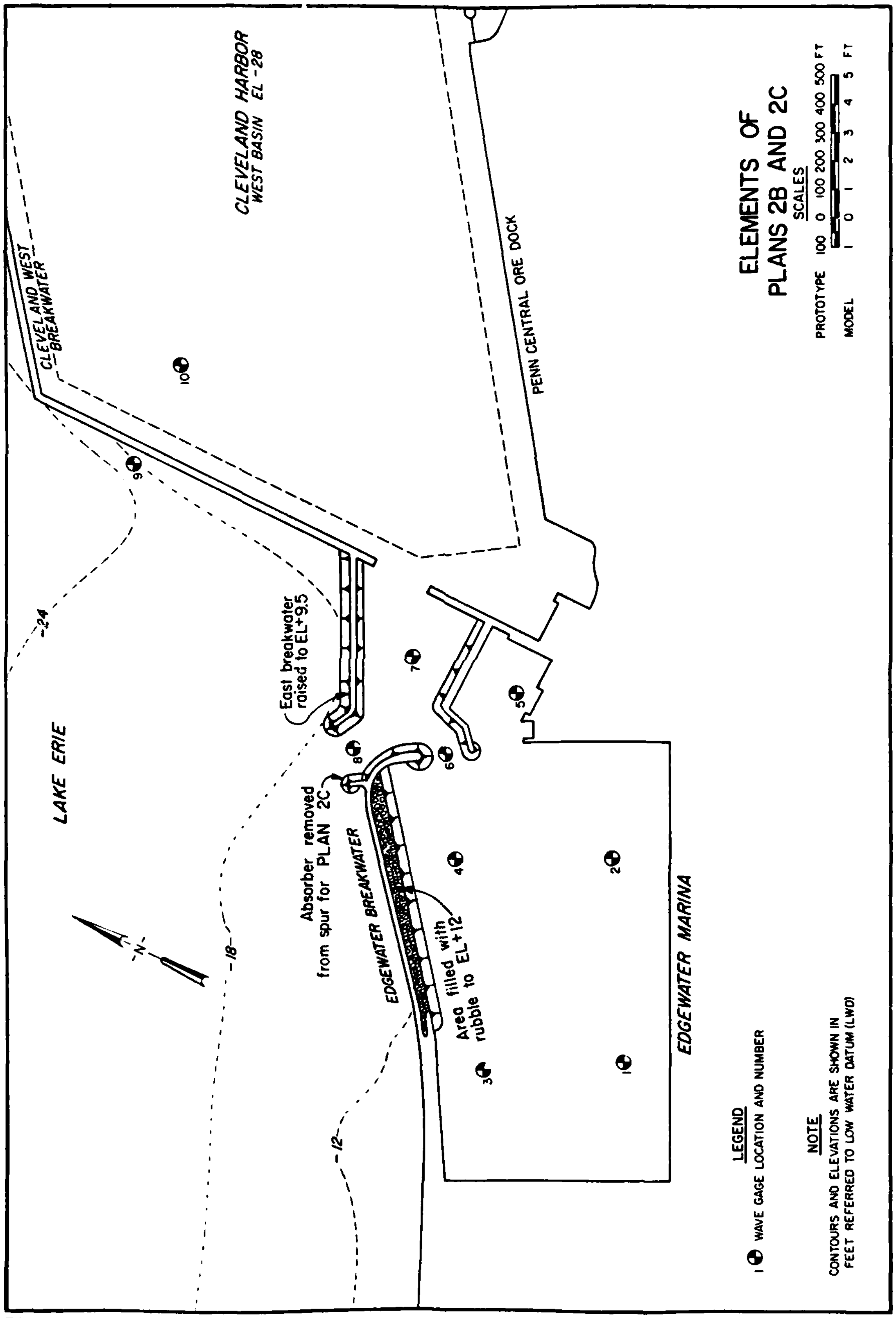
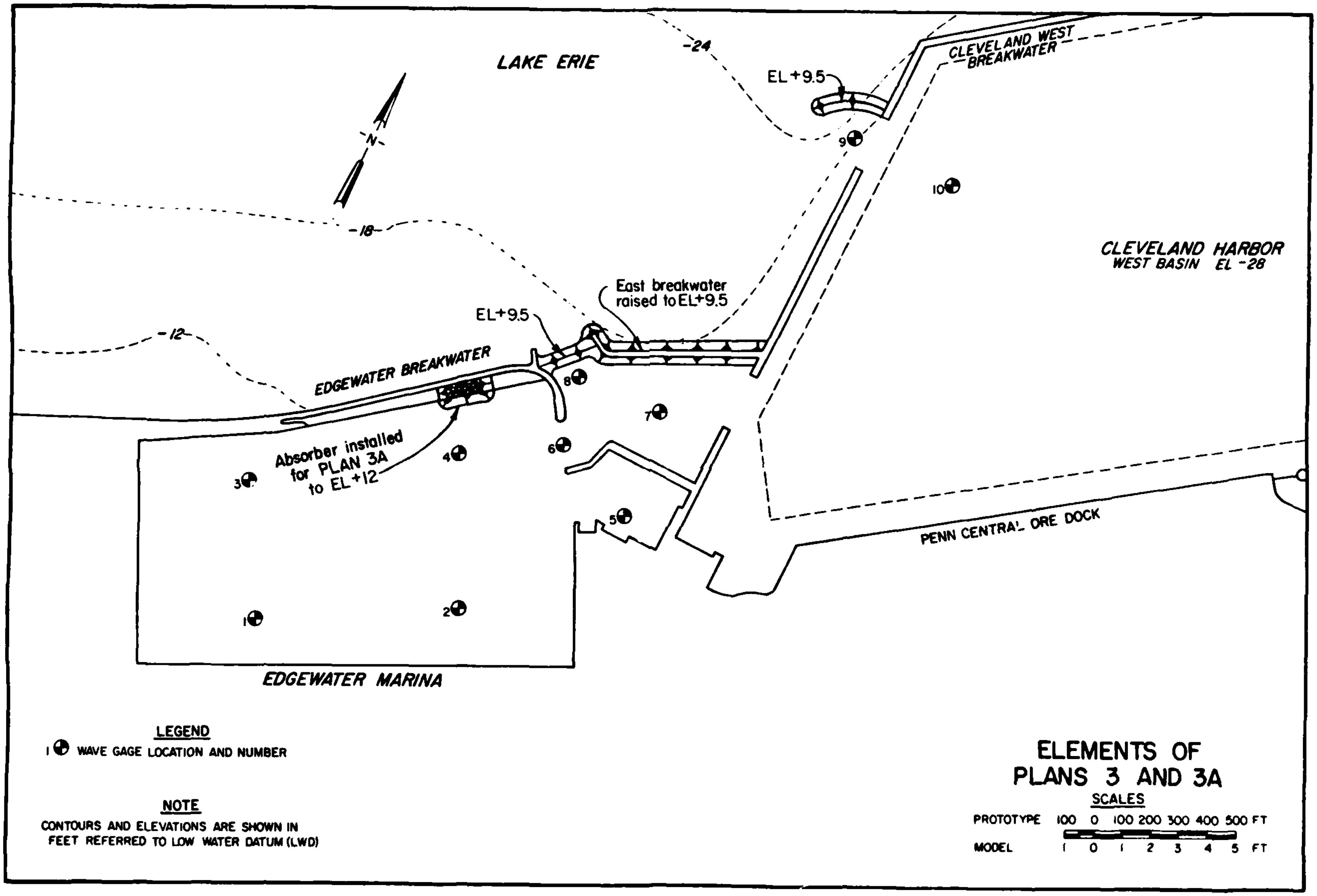

LAKE ERIE
-24
-18
-12
N
CLEVELAND WEST BREAKWATER
CLEVELAND HARBOR
WEST BASIN EL -28
East breakwater raised to EL+9.5
EDGEWATER BREAKWATER
Area filled with rubble to EL+12 and absorber installed for PLAN 2A
PENN CENTRAL ORE DOCK
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
ELEMENTS OF
PLANS 2 AND 2A
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT

PLATE 7


ELEMENTS OF
PLANS 2B AND 2C
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
LAKE ERIE
East breakwater raised to EL+9.5
Absorber removed from spur for PLAN 2C
EDGEWATER BREAKWATER
Area filled with rubble to EL+12
EDGEWATER MARINA
N
-24
-18
-12
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)



LAKE ERIE
N
-24
-18
-12
EL+9.5
CLEVELAND AND WEST BREAKWATER
East breakwater raised to EL+9.5
EL+9.5
EDGEWATER BREAKWATER
Absorber installed for PLAN 3A to EL+12
CLEVELAND HARBOR
WEST BASIN EL -28
PENN CENTRAL ORE DOCK
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
ELEMENTS OF PLANS 3 AND 3A
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT

PLATE 9

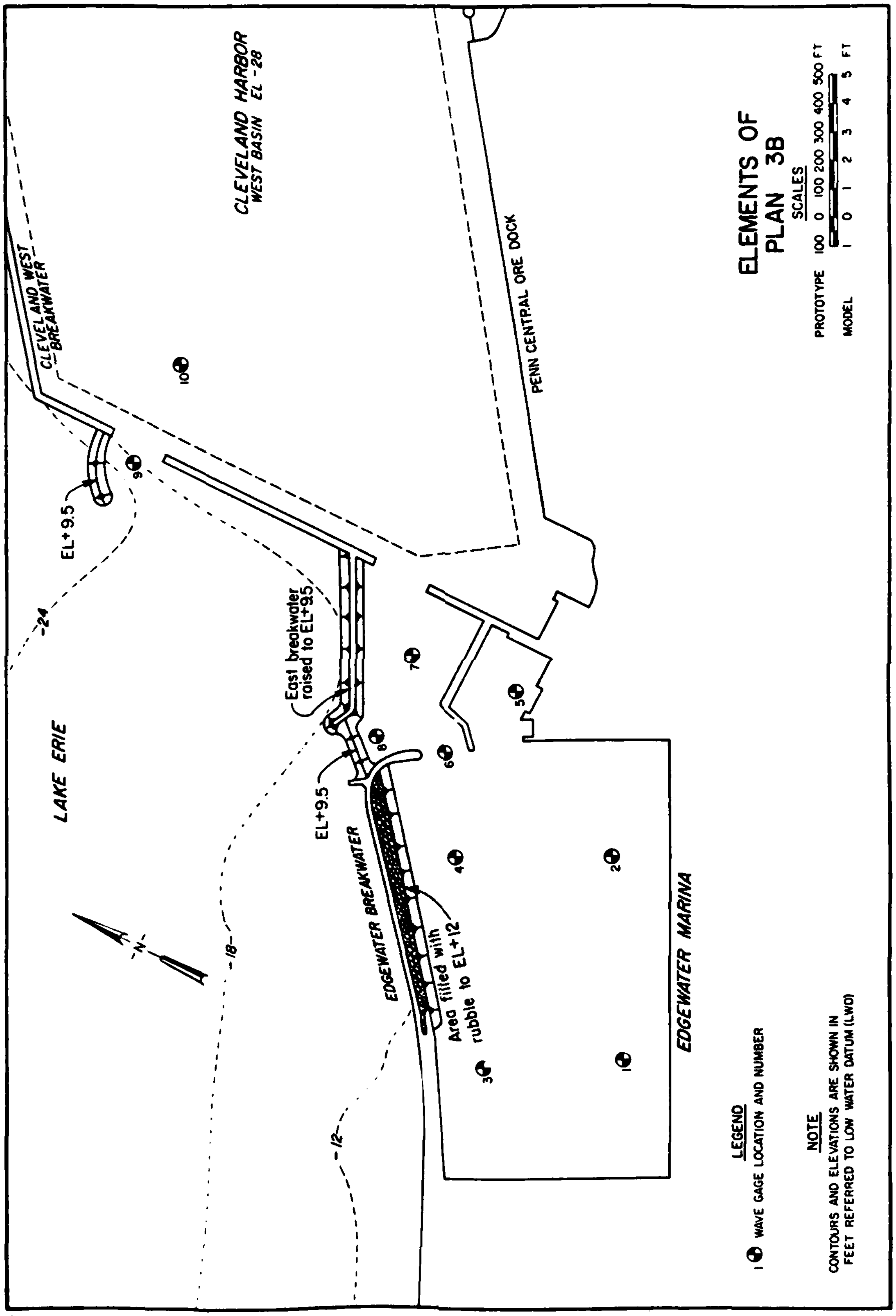
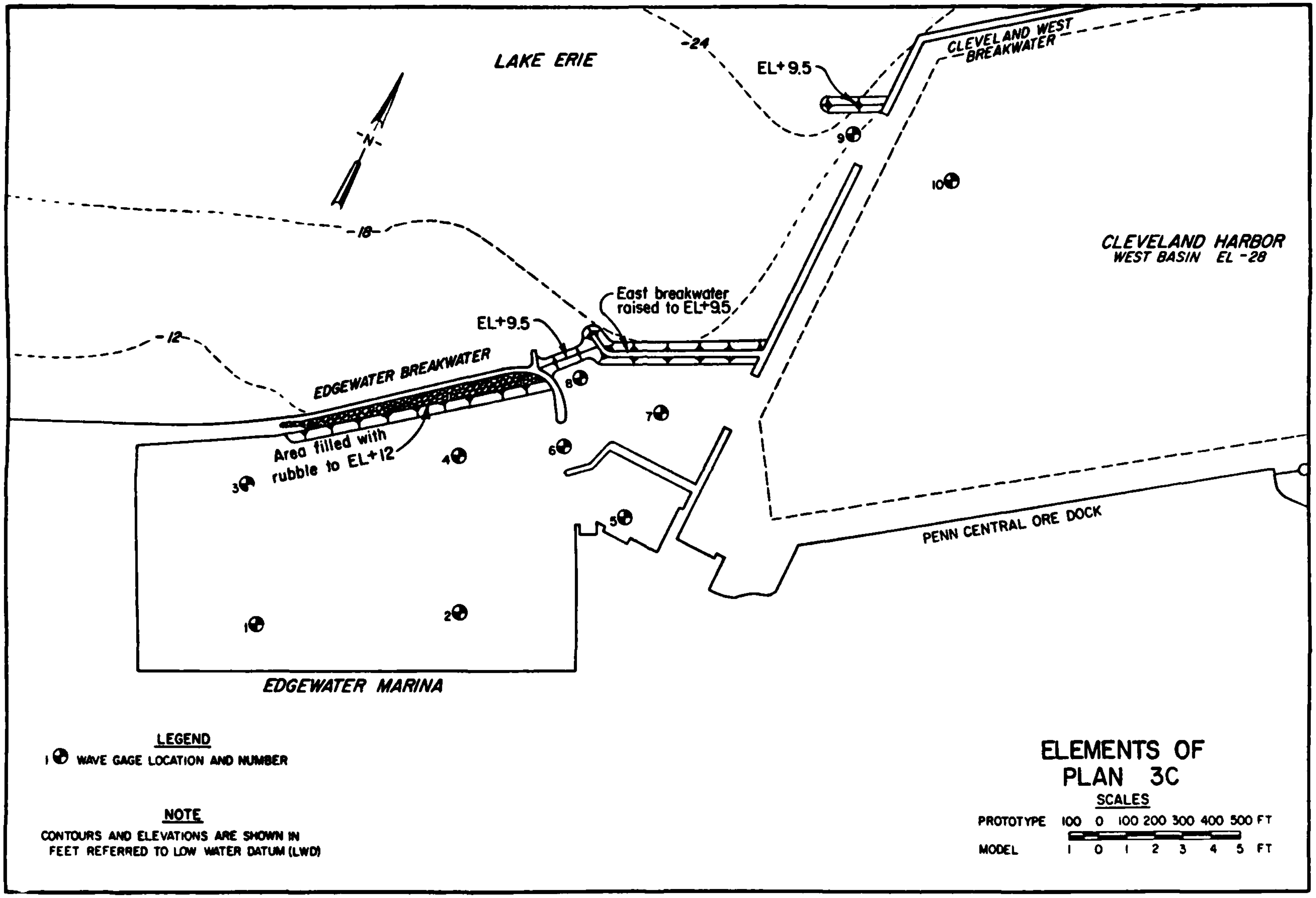
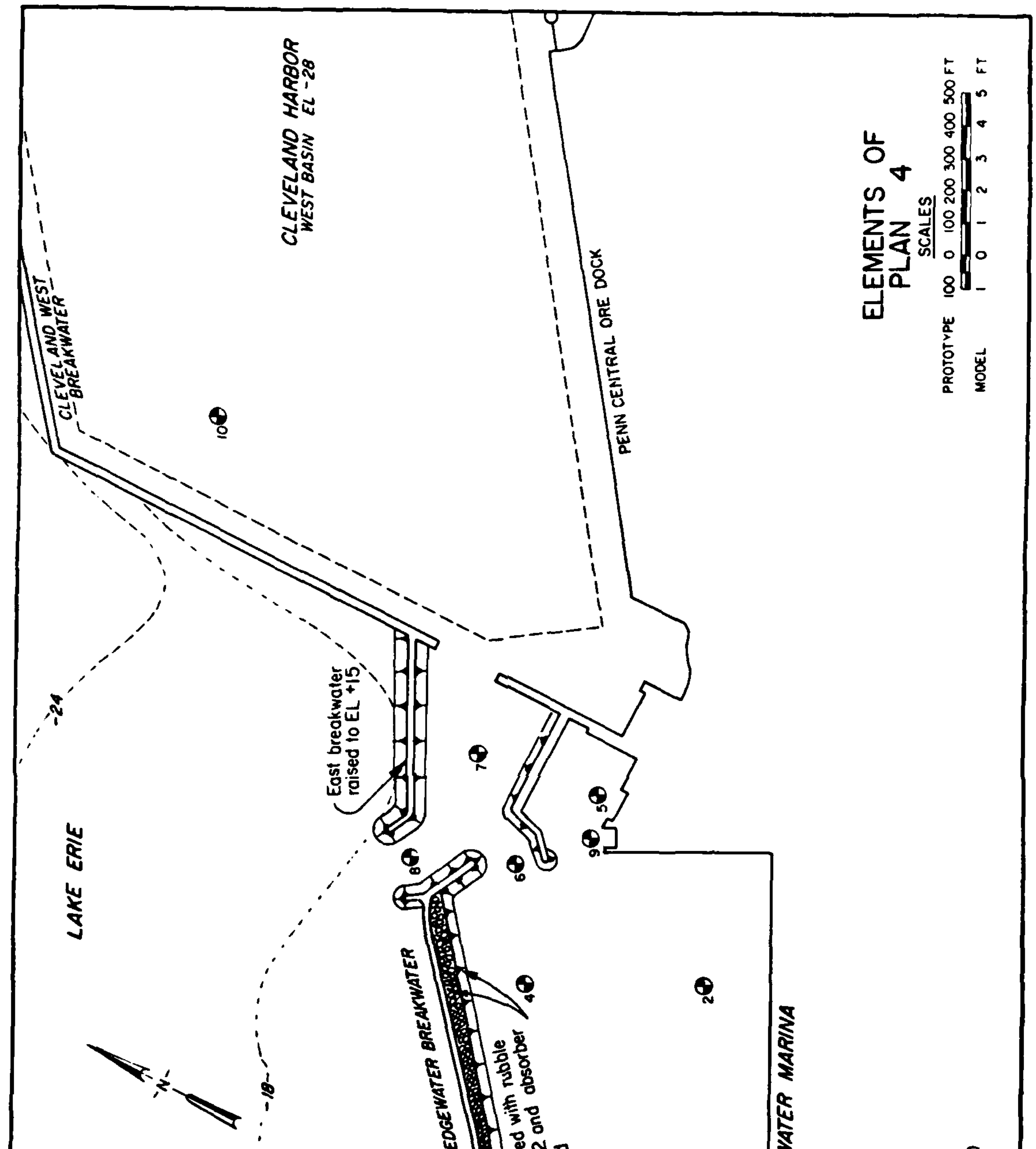
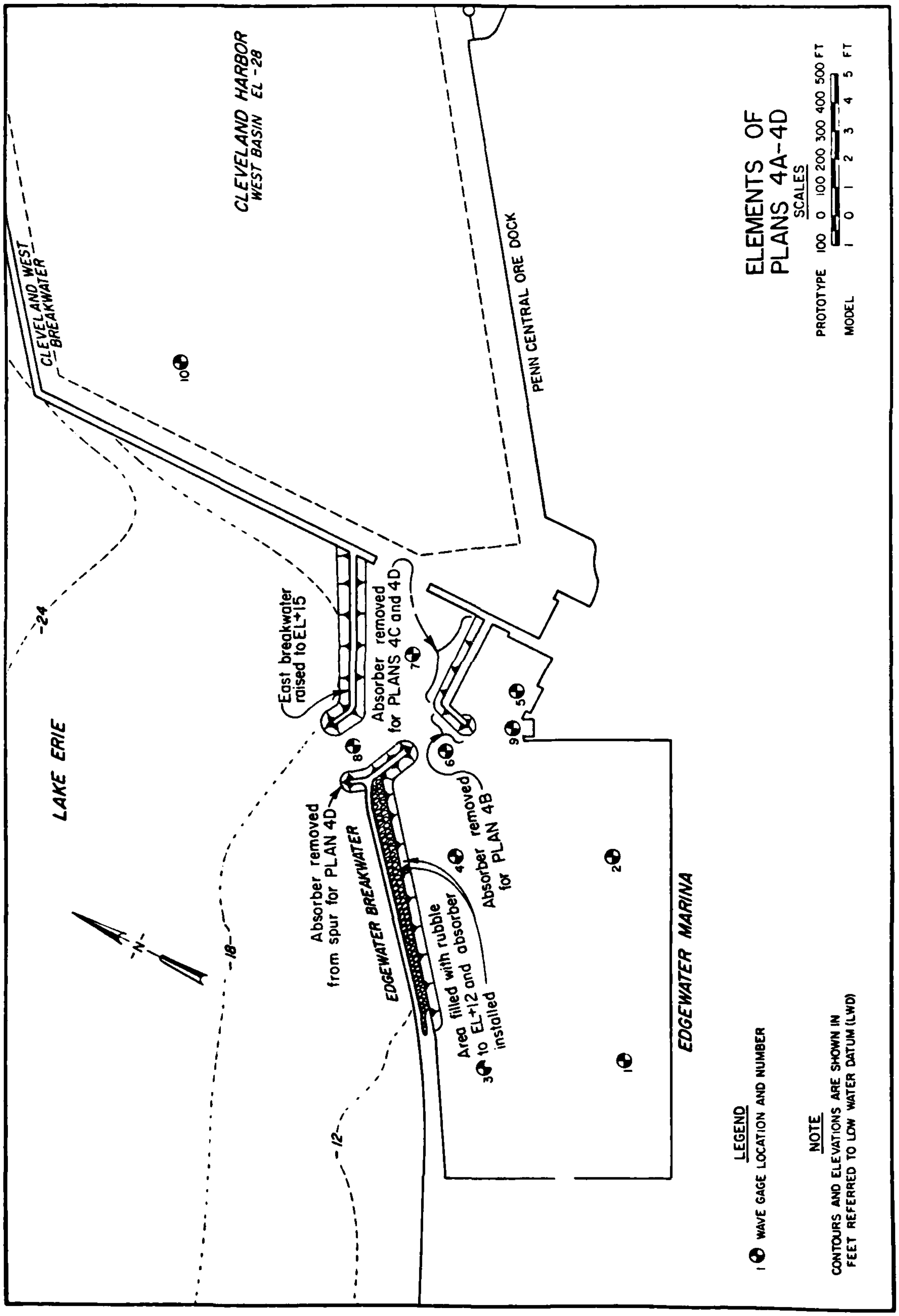

CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
ELEMENTS OF PLAN 3B
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
EL+9.5
-24
East breakwater raised to EL+9.5
LAKE ERIE
EL+9.5
EDGEWATER BREAKWATER
Area filled with rubble to EL+12
EDGEWATER MARINA
-18
-12
N
LEGEND
WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)

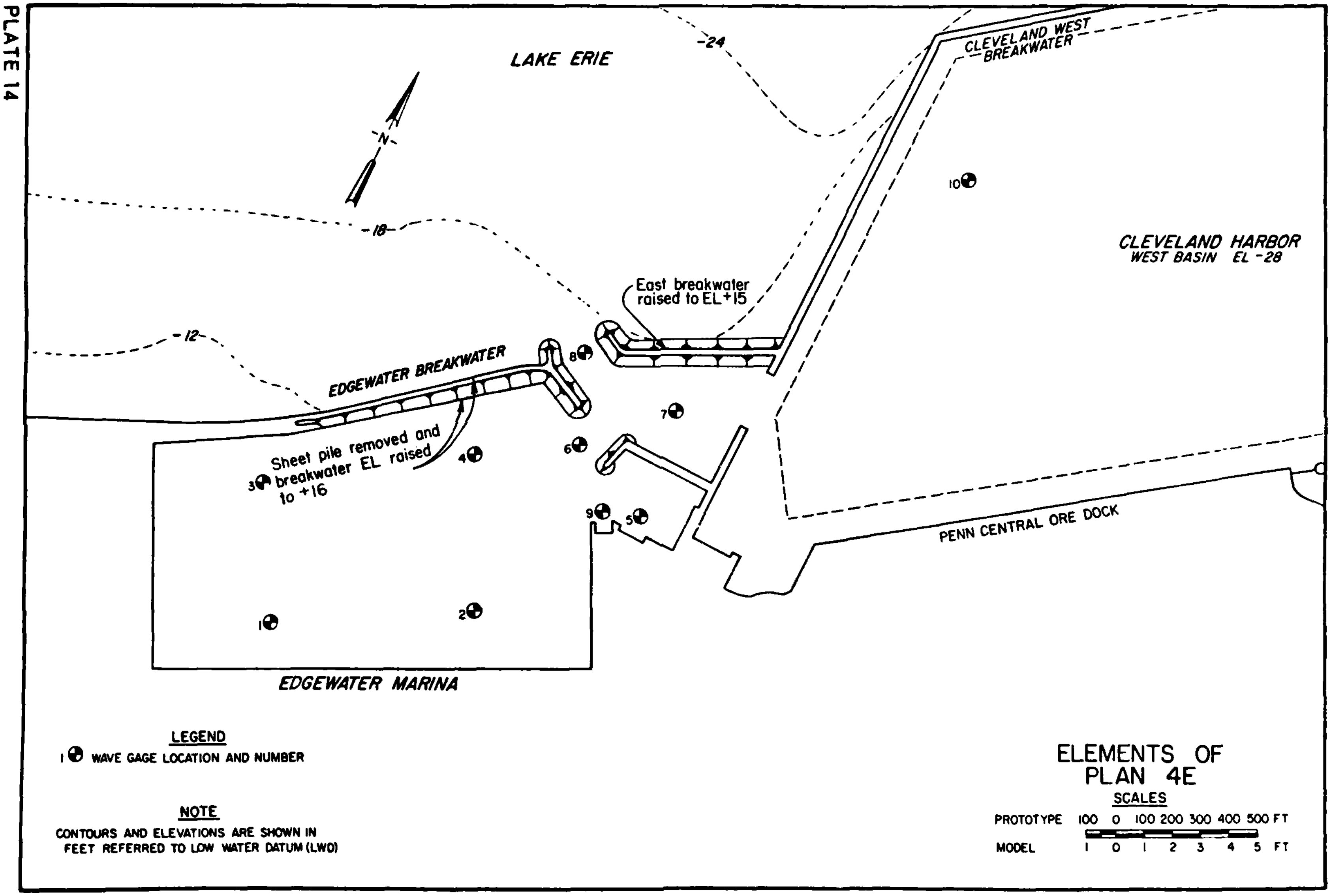
PLATE 10


LAKE ERIE
N
-24
EL+9.5
CLEVELAND WEST BREAKWATER
9
10
CLEVELAND HARBOR
WEST BASIN EL -28
-18
-12
East breakwater raised to EL+9.5
EL+9.5
EDGEWATER BREAKWATER
8
7
6
Area filled with rubble to EL+12
4
3
5
PENN CENTRAL ORE DOCK
1
2
EDGEWATER MARINA
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
ELEMENTS OF PLAN 3C
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT


ELEMENTS OF PLAN 4
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
LAKE ERIE
East breakwater raised to EL +15
EDGEWATER BREAKWATER
Area filled with rubble to EL+12 and absorber installed
EDGEWATER MARINA
N
-24
-18
-12
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
PLATE 12



CLEVELAND HARBOR
WEST BASIN EL -28
CLEVELAND WEST BREAKWATER
PENN CENTRAL ORE DOCK
ELEMENTS OF
PLANS 4A-4D
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT
LAKE ERIE
N
-24
-18
-12
East breakwater raised to EL+15
Absorber removed for PLANS 4C and 4D
Absorber removed from spur for PLAN 4D
EDGEWATER BREAKWATER
Area filled with rubble to EL+12 and absorber installed
Absorber removed for PLAN 4B
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)


LAKE ERIE
N
-24
-18
-12
CLEVELAND WEST BREAKWATER
CLEVELAND HARBOR
WEST BASIN EL -28
East breakwater raised to EL +15
EDGEWATER BREAKWATER
Sheet pile removed and breakwater EL raised to +16
PENN CENTRAL ORE DOCK
EDGEWATER MARINA
1
2
3
4
5
6
7
8
9
10
LEGEND
1 WAVE GAGE LOCATION AND NUMBER
NOTE
CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
ELEMENTS OF
PLAN 4E
SCALES
PROTOTYPE 100 0 100 200 300 400 500 FT
MODEL 1 0 1 2 3 4 5 FT

APPENDIX A: NOTATION

A	Area
b	Shallow-water othogonal spacing
b_o	Deepwater orthogonal spacing
$(b_o/b)^{1/2}$	Refraction coefficient, K_r
H	Shallow-water wave height
H_o	Deepwater wave height
$H_{1/3}$	Significant wave height
K_r	Refraction coefficient
K_s	Shoaling coefficient
L	Length
T	Time
V	Velocity
$\forall$	Volume

END

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